Ultra low energy museum storage

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Summary: *Museum stores in temperate climates are best built with lightweight insulated walls and roof, resting on a floor in direct contact with the ground and without insulation. Solar powered dehumidification operates during the summer. The smaller demand for winter dehumidification and occasional humidification is achieved by humidity buffering. This concept depends on museum standards for temperature, which currently demand constancy through all seasons, being relaxed to allow a gentle annual cycle in temperature.*

Keywords: *storage, dehumidification, humidity buffering, thermal buffering, solar, energy*

Introduction

There is a widespread assumption that greater risk must be accepted if we allow the widening of environmental limits for display and storage of art and artifacts. We take the more optimistic view that much money and complexity of climate control apparatus can be saved without increasing the risk, or rate of damage to artifacts. On the contrary, building for climate stability within a gentle annual cycle of temperature and relative humidity (RH) makes a safe environment, able to cruise through periodic crises in maintenance and fuel supply.

We present a concept of storage design which starts with the building as an environmentally calm and stable container, requiring minimal energy and complexity to maintain a moderate climate. The fundamental concepts that need to be merged to design a naturally safe museum are these:

- An indoor temperature which follows, with reduced amplitude, the annual cycle of outdoor temperature.
- Thermal inertia, to even out the daily variation in outside temperature and the heat emitted by people, lighting and recirculating air pumps. Thermal inertia and thermal insulation must be matched according to the local climate. The ground is also used as a thermal buffer, moderating the yearly climate cycle.
- Thermal uniformity of the building interior, so that the temperature throughout a room is naturally uniform, needing no forcible circulation of air to even out the temperature. This will automatically secure a uniform RH.

- Very slow air exchange rate. This prevents unruly weather from disturbing the internal microclimate. However, deliberate intermittent pumping of air can be used to steer the interior climate towards a set point.
- Because of the generally low air exchange rate, internal air pollution must be minimised. Outside air pollution becomes much less important an agent of decay.
- A minimal air exchange rate will allow the use of humidity buffers, which in turn allows the use of intermittent dehumidification driven by solar energy.

We discuss these points in turn.

The museum standard for temperature

The storage microclimate can be optimised for the artifacts with scant regard for human convenience. We can divide artifacts according to their natural rate of decay and segregate unstable objects in a cold store. More robust art can be housed in stores with a temperature which follows the annual climate cycle, reduced by thermal buffering. Current museum standards such as BS5454:2000 demand year-round temperature constancy but there is no evidence that artifacts suffer from a slowly varying temperature over a moderate range. Indeed we have evidence that damage is rare, even when artifacts are plunged suddenly from 20 °C to -30 °C to kill bugs that may be hitching a ride into the store room from exhibition rooms in faraway places. Furthermore, film has been stored for decades at sub zero temperature, with no evidence of damage, even after repeated excursions to room temperature. The temperature constancy demanded by some standards expresses excessive optimism about what can be achieved and unwarranted pessimism about the danger of not achieving it.

Storage climate

We present here the 'Copenhagen model' for museum storage. This is an insulated lightweight superstructure sitting on a concrete floor laid directly onto the ground. It is dehumidified by solar power. The store is on a single level and low compared with its footprint, though perforated mezzanine levels are permissible. The floor functions as a year round temperature buffer. The insulated superstructure functions as a barrier to the daily temperature cycle outside. This combination will, unaided, result in too high an inside relative humidity (RH) in most climates. The RH is customarily reduced in two ways, by heating to about six degrees above the ambient temperature, or by dehumidification. We recommend dehumidification, combined with great attention to airtightness, so the load on the dehumidifier is minimised. Chemical decay is reduced by dehumidification compared with heating to achieve the same constant RH (commonly called conservation heating). A further refinement is to drive the dehumidification by solar power. This is abundant in the summer, when the dehumidification load is greatest, because the summer temperature indoors will be lower than that outside. The winter RH is moderated by the relatively high winter temperature indoors. A moderate amount of humidity buffering by the contents and by the building materials will maintain a stable RH even with the intermittent energy provided by solar power. Humidification will never be necessary.

The museum store at Ribe, southern Denmark

An example of a building which comes close to exemplifying the model sketched above is the storage building at Ribe in southern Denmark (Figure 1).

Figure 1: *The museum storage building in Ribe, south Denmark. Architect Bo Christensen ApS.*

It was brought into use early in 2007. The store is 42 × 24 m in floor plan and 6.5 m high. The 740 mm walls contain 250 mm of mineral wool insulation encapsulated between layers of brick and concrete, all separated by small air gaps. The roof contains 300 mm of mineral wool, while the concrete floor is not insulated. The store has an air exchange rate about once in 33 hours. There is no heating in the store, but some heat leaks in from adjacent offices and from fans which re-circulate the air through the dehumidifier, which also releases heat.

The temperature in the storage area varies between 10 °C and 16 °C in an annual cycle. The relative humidity is maintained at about 50% by mechanical dehumidification (Figure 2). The energy needed for maintaining this indoor climate is less than two kWh per cubic metre of storage space per year (Ryhl-Svendsen et al. 2010).

Such a building, with one large storage area, kept at a low air exchange rate, and placed directly on the ground, is thermally influenced by heat transfer through the walls and the floor. The better the insulation toward the air, the more the temperature is dominated by heat transfer through the floor. With highly insulated walls and roof the floor will always be cooler than the room during summer, and warmer than the room during winter.

Figure 3 shows temperature profiles through the floor in the centre of the Ribe store, and a parallel profile taken below open ground beside the building. The floor is evidently acting as a heat sink independent of the temperature gradient which prevails under open ground. Even the profile one metre in from the outside wall is close to that in the centre of the floor.

The annual cycle is at a higher average temperature than outside, because of the sources of heat within the building. The green area on the graph represents the excess water vapour concentration outside (above the zero line) which has to be removed by dehumidification. The RH is held between 55% and 60% all through the year. Notice the greater excess water vapour during the summer, because the interior is below ambient temperature. Fortunately, this is the time when solar energy for dehumidification is abundant.

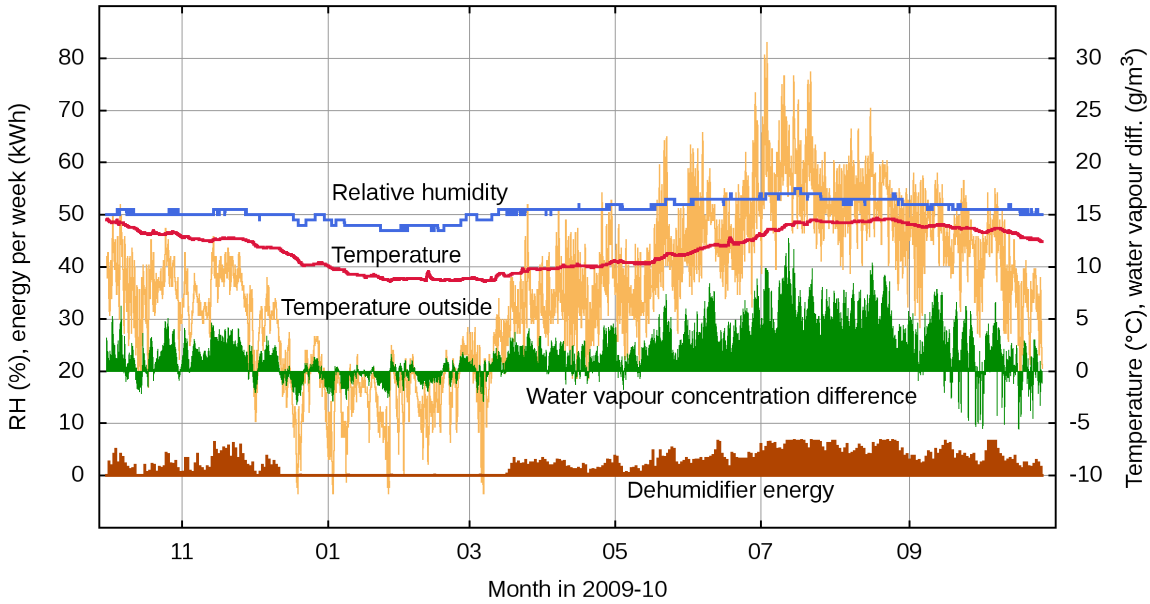

Figure 2: *The temperature and RH within the Ribe store. The dehumidifier works mostly in summer, suggesting the possibility of driving it by solar power.*

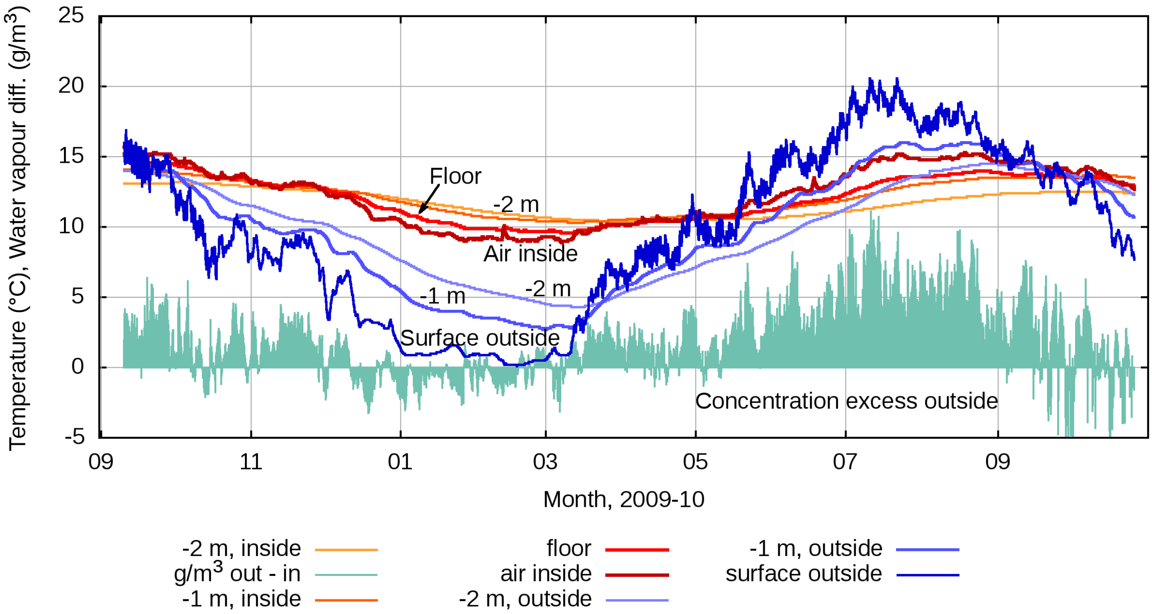

Figure 3: *The course of the temperature in, below and beside the Ribe store during one year. The two sets of coloured traces mark the temperatures at 2 m and 1 m depths and at the surface, in the middle of the building and at a point 25 m away from the building in an open field. The temperature deep under the floor in the centre of the building is largely influenced by the annual cycle of temperature within the building. Even the temperature profile measured one metre inside the wall shows only a small influence by the outside temperature (not shown on the graph). There is very little heat transfer from beyond the perimeter of the building. The light blue area indicates the excess water vapour concentration outside, when it is above the zero line.*

In winter there are occasions when humidification is indicated, but humidity buffering by the contents, or by building materials, allows the interior climate to continue with only a slow, insignificant fall in RH.

Summer dehumidification

The dehumidification burden can be calculated from the air exchange rate and the excess water vapour in the infiltrating air. Allowing for humidity buffering to even out the burden, one must have capacity to remove 5 g per hour (h), per cubic metre, per air change. A realistic air change rate for a large store is 0.05 h^{-1} so the capacity needed is 0.25 $g/h{\cdot}m^3$. The heat of condensation of water is 2.26kJ/g, so the energy demand is 0.6 $kJ/h{\cdot}m^3$ = 0.00017 $kWh/h{\cdot}m^3$. However, practical dehumidifiers are not totally efficient, so one must allow 0.0002 $kWh/h{\cdot}m^3$. For solar heating in summer in a cloudy climate one can conservatively assume an energy gain of 1 kWh per day per square metre of absorber. This averages to 0.04 kWh/h. So each cubic metre of storage space requires 0.004 m^2 of solar collector. For an 8 m high building, each square metre of roof requires 0.05 m^2 of solar collector. That is 5% of the roof area, an entirely practical arrangement.

The dehumidifier envisaged is the type which re-circulates room air through a cylinder of desiccant. When the desiccant becomes damp, the room air circuit is stopped and outside air is blown through the desiccant while the cylinder is warmed by water from the solar heater. The control system should ensure that periods of sunlight are used for regeneration, even when the desiccant is not fully exhausted. RH buffering will ensure that the intermittent operation of the dehumidifier does not cause significant variation in RH.

Humidity buffering

Solar dehumidification needs buffering by hygroscopic materials in the room. Both artifacts and the building materials contribute. For buildings with a slow air exchange rate, the buffer capacity can be calculated from the sorption curve of the material. Measurements by Padfield and Jensen (2011) show that the most effective building material is unfired brick. The sorption, as measured in weight change per change of RH unit is not easily translated into buffer performance when the ventilation rate strains the ability of water to diffuse through the buffer material. Padfield and Jensen have proposed a measure of buffer performance called the Buf (symbol B). This is the moisture absorption of the buffer consequent on a change in RH, expressed as the equivalent volume of space which will accept the same amount of water vapour when subjected to the same RH change. The advantage of this way of expressing buffer capacity is that one can calculate RH change in the room due to air infiltration by calculating a smaller, 'virtual' infiltration rate which is the actual rate divided by the B value. The Ribe store has no deliberate buffering but one can calculate the consequence of building with the rooms lined with unfired brick. It is feasible, with this material used as a 50 mm veneer on all the walls to achieve a B-value around 25. This means that the change of RH caused by infiltration is reduced to one twenty fifth of that caused by infiltration into a water-inert room. An archive which is full of paper documents will attain a B-value around 200. Figure 4 shows the predicted course of the RH in an unbuffered store (B=1) and in buffered stores at various B-values. On close analysis, a very large B-value is not advantageous when combined with a dehumidifier.

It is clear from figure 4 that some deliberate buffering is needed, but not so much as to significantly reduce the volume available for storage.

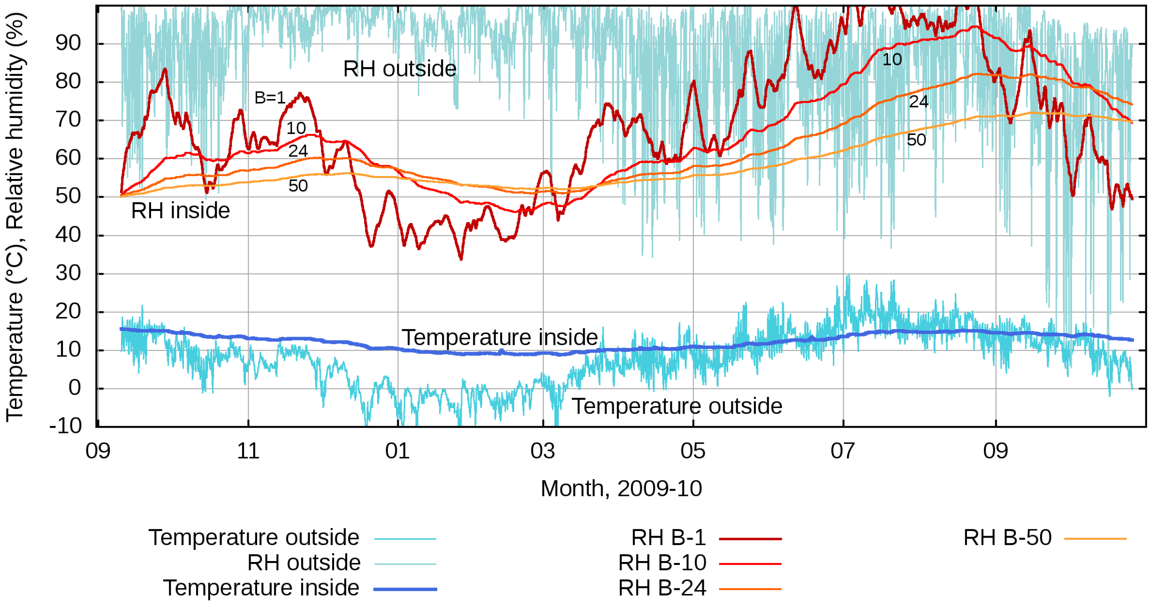

Figure 4: *The Ribe store modeled without dehumidification, but with varying degrees of humidity buffering. The air change rate is 0.03 per hour. The RH is arbitrarily set to 50% at the beginning of the period, so the initial rise in RH shows the effect of stopping the dehumidifier, with different amounts of humidity buffer.*

Comparison of dehumidification with heating to constant RH

Conservation heating has been used to reduce the RH in museums which are closed in winter. In northern Europe this leads to an indoor temperature cycle with the same amplitude as that outside but about six degrees warmer. The higher summer temperature will cause a disproportionate increase in deterioration rates, because of the kinetics of many chemical reactions. Dehumidification allows a much flatter annual temperature cycle. In principle this cycle could be centered on the annual average outdoor temperature but in practice there are always heat sources within a building. In Ribe, the heat production is about one kilowatt. This means that there is an element of conservation heating even in the dehumidified building. The distinctive feature of the dehumidified building is that it has a small annual temperature cycle, at a lower average value than that of conservation heating. Humidity buffering can be invoked to reduce the temperature cycle of both methods. A second difference between the two methods is that conservation heating needs the most energy in winter, because the outside RH is highest in winter, while dehumidification needs the most energy in summer, when solar energy is abundant. Humidity buffering allows intermittent operation of the dehumidifier, which is inevitable if solar energy is used. For these reasons, we concentrate on the development of the dehumidification principle for museum storage.

Air pollution

The low air exchange rate that is essential to our model of climate control in museum stores reduces the harm done by pollutants generated outside the building but increases the concentration of internally generated pollutants.

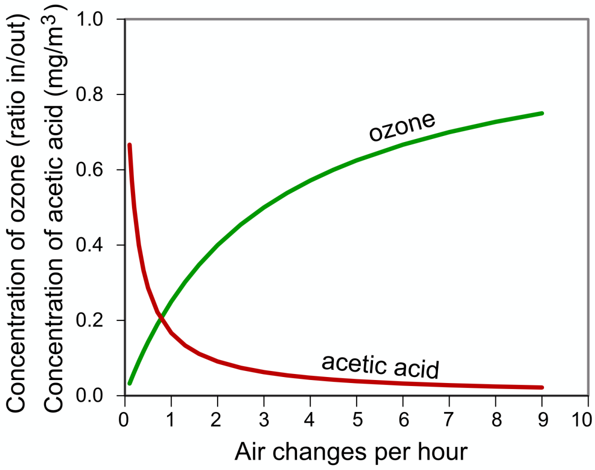

Figure 5: *Modeled concentrations indoors of ozone infiltrating from outside and acetic acid released at a constant rate from inside. A ventilation rate between once and twice per hour is enough to substantially reduce the concentration of internally generated pollutants.*

This can be illustrated using data for ozone, originating outside, and for acetic acid vapour, originating inside. Figure 5 shows how the indoor concentration of ozone diminishes with reduced air exchange rate. This is because the ozone that does come in reacts quickly. Evidently, the smaller the air exchange the less reaction there is with the collection. The opposite happens with internally generated pollutants. The curve for acetic acid concentration, based on a constant flux of acid vapour from slow decomposition of the collection, shows a very high concentration in an unventilated space. The absorption of acetic acid by the room contents is slow compared with ozone; the reduction in concentration is mainly due to escape of acetic acid to the outside (Ryhl-Svendsen 2006).

Two air changes per hour is enough to reduce the acetic acid concentration. This concentration reduction can easily be achieved by recirculation at the same rate through a carbon filter, which will use much less energy than ventilating with conditioned new air.

Discussion and conclusion

We have combined measured records from an existing building with predictions for the behaviour of an optimised museum store which uses a combination of thermal resistance in the walls and roof, thermal capacity in the floor, humidity buffering and intermittent solar powered dehumidification. It seems perfectly feasible to construct an ‘off-grid’ museum store, entirely air conditioned without combustible or cable fed energy.

Acknowledgements

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Notes

1. Calculation of humidity buffering by unfired brick walls. According to Padfield and Jensen (2011), a 50 mm thick perforated unfired brick has a B-value of about 100 for slow RH changes.

This means that each square metre of brick surface has equivalent absorption to 100 cubic metres of air (strictly speaking 100 m^3 of space). If, for example, one supposes the Ribe building divided into three equal compartments by putting two internal walls across the building, the total area of brick is 500 m^2, equivalent to 50000 m^3 of space in its buffer capacity. The actual space is about 2200 m^3, so the ratio of virtual volume to actual volume is 552200/2200 = 24. Next, the actual infiltration rate, 0.03 air changes per hour, is re-calculated to a virtual air exchange rate of 0.03/24 = 0.0013. This is the infiltration rate used to calculate the change in RH of inside air as a result of air exchange with the outside. Note that this calculated virtual volume does not apply to heat transfer through air infiltration, where the actual rate is used.

2. The pollution model is based on a mass-balance equation between the amount of pollutant which is introduced to the room (infiltrating with outdoor air, or being generated as off-gassing within the room), and the amount which is removed from the room (by ventilation and by surface reaction). The surface removal rate is defined as the deposition rate of the pollutant (m/s) onto a surface, multiplied by the surface-to-volume ratio of the room (m^2/m^3), which gives surface removal rate the unit of reciprocal time. The surface removal rate is directly comparable with the air exchange rate, and reflects the amount of pollutant which is deposited on surfaces in terms of room volumes per unit time. The deposition velocity is a property of the pollutant and the surface, and describes the rate of loss of a pollutant from the air to the surface. For the graph we used typical indoor values: 1.5 m/h for ozone, and 0.2 m/h for acetic acid. At the same time we assumed a constant rate of generation of acetic acid within the room, and a constant concentration of ozone outdoors. See also Ryhl-Svendsen (2006) for a general discussion of pollution modeling.

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