A museum storage facility controlled by solar energy

Morten Ryhl-Svendsen, Lars Aasbjerg Jensen,
Poul Klenz Larsen, Benny Bøhm and Tim Padfield

Abstract

We present a model for a museum storage building which controls its climate by solar heating. The temperature is moderated by heat storage in the ground below the floor while a highly insulated superstructure and good airtightness shields against variation in weather. The relative humidity is kept moderate by solar heating of the attic space through a roof window. The heat is slowly released through the ceiling to the storage space below. This will give a temperature which cycles annually between 10 °C and 25 °C. Fine humidity control can be achieved by use of moisture reactive wall surfaces, such as clay in the form of unfired brick.

Introduction

We present a model for a museum storage building which controls its climate by solar heating. The temperature is moderated by heat storage in the ground below the floor while a highly insulated superstructure and good airtightness shields against variation in weather. The relative humidity is kept moderate by solar heating of the attic space through a roof window. The heat is slowly released through the ceiling to the storage space below. This will give a temperature which cycles annually between 10 °C and 25 °C. Fine humidity control can be achieved by use of moisture reactive wall surfaces, such as clay in the form of unfired brick.

The operating principle of the passive store

1. The temperature cycle through the year is moderated by massive buffering by the floor, which is laid on the ground without insulation. This means that the floor area must be large and the store must be single storey, though perforated mezzanine platforms are permissible.

2. The influence of day to day weather is minimised by an airtight, well insulated building envelope above ground. This may be lightweight, since

thermal inertia is provided by the ground and to some extent by the collection objects.

3. The relative humidity (RH) is buffered by extensive use of moisture reactive wall surfaces, for example unfired brick used as a veneer or as a wall construction material.

4. The tendency towards too high a relative humidity is compensated by solar heating of the attic space, with slow release of heat through a massive ceiling. Solar heating is greatest during the summer, so both humidity and temperature buffering are essential to avoid a damaging high summer temperature.

The low energy storage building

Some of these characteristics are already present in museum stores; some have been explored in small experimental constructions and some are only computer generated predictions. In this article we base our argument on an existing storage building in Ribe in south west Denmark, extending its measured performance by computer simulation to move a step further towards low-energy, fully passive climate control.

Figure 1: The storage building for the Museums of South West Denmark, in Ribe. Architect: Bo Christensen ApS, Engineers: Birch and Krogboe A/S. Opened in 2005.

Temperature control

In Denmark a well-insulated but lightweight single storey building with an uninsulated floor laid directly on the ground will provide an annual temperature cycle between about 7 °C and 15 °C, averaging 12 °C (Fig. 2). The building envelope shields against the rapid changes in weather, while the ground below the floor acts as a heat store, which allows the indoor air temperature to follow the annual temperature cycle outdoors with reduced amplitude.

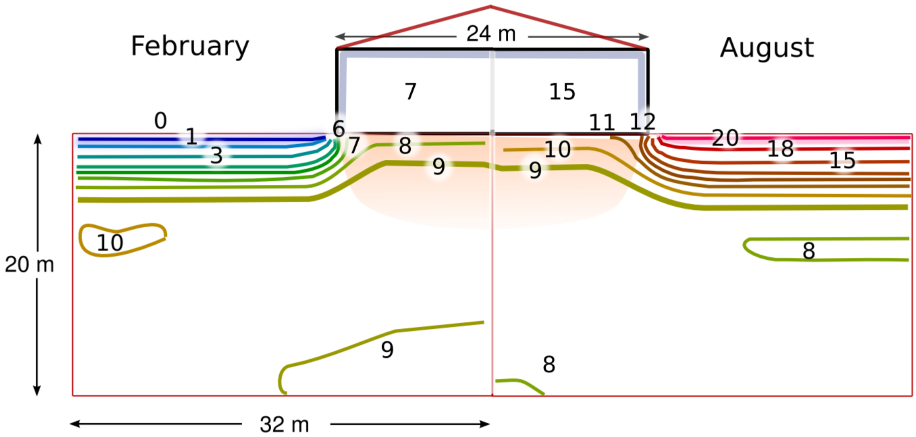

Figure 2: Temperature buffering by the ground beneath a large building. The store has well insulated roof and walls but the floor is uninsulated. On the left is the Danish winter situation with an inside temperature of 7 °C in February. To the right is the summer situation with 15 °C indoors in August. The ground acts as a heat source in winter and as a heat absorber in summer. As years go by, the ground under the building approaches the annual average temperature within the building, regardless of the natural climate outside. Technical details of the computer simulation are given in the appendix.

Humidity control by mechanical dehumidification

The relatively low temperature indoors in summer will result in too high a RH, so mechanical dehumidification is used in the Ribe building. Due to a very low air exchange rate (less than 1 per day), which minimizes the infiltration of excess moisture, a stable RH at 50% can be maintained throughout the year for about 2 kWh per cubic metre of storage space. This is the measured energy consumption of the Ribe storage.[1,2]. A benefit of the low air exchange rate is that the infiltration of pollutants is very slow. However, internally generated pollutants may then accumulate but can be removed by recirculating air through a sorbent filter, or by passive sorption on a reactive wall material [2–5].

Up to three-quarters of the energy consumed is used by the dehumidification process and the rest is used by the air recirculation fans. In the 6500 m^3 storage building in Ribe, a 2 kW absorption dehumidifier runs almost constantly from July to September. However, during the winter it is inactive for

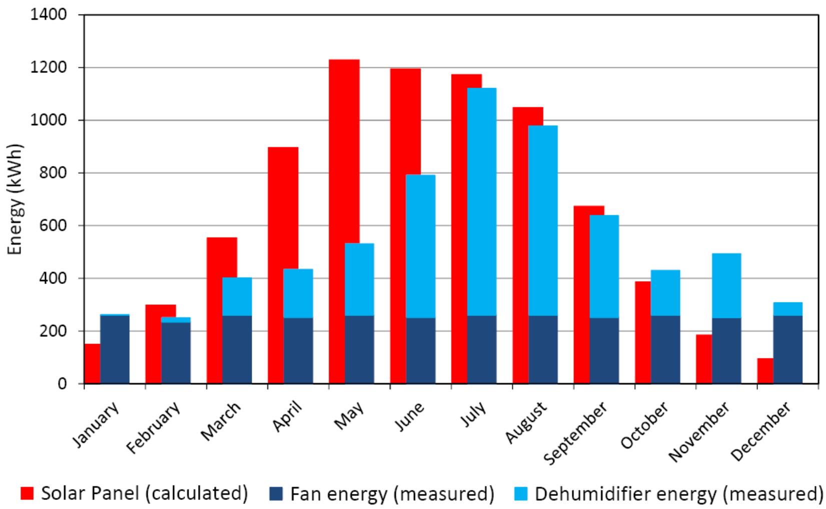

Figure 3: The monthly energy used for air conditioning in Ribe (measured in 2009-2010), compared with the predicted energy provided by a solar panel (12% efficiency) covering 5% of the roof area and facing south.

weeks at a time. The building is today connected to the energy grid, but it is tempting to imagine a set-up in which the building can be energy independent and operate totally off-grid.

Energy from solar panels

At present, mains electricity is used for dehumidification. The consumption is mainly during the summer, so solar energy is an obvious source. Fig. 3 shows the energy used for air conditioning in the Ribe building, based on measurements from 2009 to 2010.

The figure also shows a prediction of the energy which would be provided by a solar panel of 12% conversion efficiency covering 5% of the roof area (60 m^2) and tilted to the south. Such an arrangement would on average provide the right amount of energy. However, there will be times when the panels produce more energy than needed (spring-summer), and other times where the production is too small to cover the fan energy, though it is always sufficient to drive the dehumidifier.

A backup connection to the main energy grid may still be advantageous, so electricity shortage or surplus can be traded in and out of the building. Recirculation for pollutant control can be intermittent, increasing when the sun shines.

Dehumidification compared with conservation heating

Dehumidification without moving parts is difficult but would provide a superior environment because the summer temperature is kept low, with consequent slowing of deterioration reactions. Typically the rate of deterioration will be about halved in a cool storage building as compared to an exhibition gallery heated for peoples' comfort. However, while this is a relevant issue especially for modern collections, other collections of more robust objects will tolerate a higher storage temperature – even for long-term storage.

If one aims at a totally passive solution, without moving parts and control electronics, an alternative is to heat the building to achieve a moderate RH. This process of controlling heating to maintain a constant RH rather than a constant temperature is called conservation heating. One way to achieve this is by direct solar heating, most conveniently provided by heating an attic above the storage room through a window in the roof. Heat then diffuses down into the storage room through a concrete ceiling.

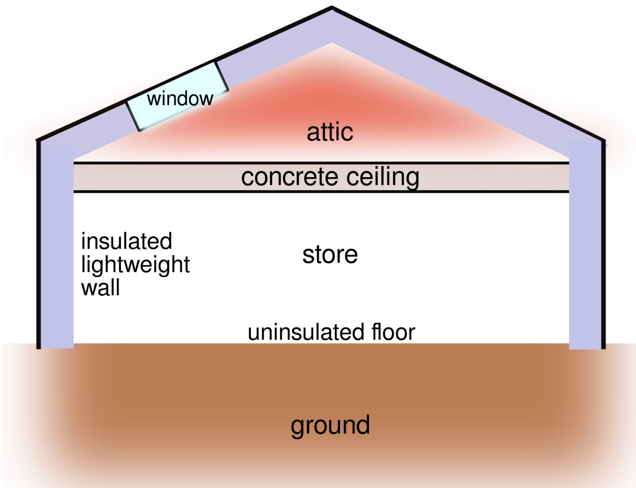

Figure 4: Uncontrolled heating is provided by sunlight through the attic window. This heats the ceiling which transfers heat slowly to the room below. This heat flow mingles with heat flow through the uninsulated floor into the massive heat sink provided by the ground. The above ground parts are highly insulated, lightweight and airtight. Dimensions and material properties are given in the appendix.

The construction is sketched in Fig. 4. The thermal mass of the ceiling will minimise the daily temperature variations, while the thermal mass of the floor will reduce the annual variation. This, in combination with a low air exchange rate and humidity buffering (discussed below), will give an annual cycle of room climate with a moderate RH but with a higher summer temperature than in a dehumidified and unheated building.

Dehumidification by solar heating

To our knowledge no museum store exists today with humidity control by solar heating. However, by computer simulation we demonstrate how a building similar to that in Ribe could be designed to maintain an annual RH variation held within the band 40% to 60% by heat gain through a roof window. The annual temperature profile is then predicted to cycle between 10 °C and 25 °C. A south facing window covering 7% of the roof area (80 m^2) will achieve that (Fig. 5).

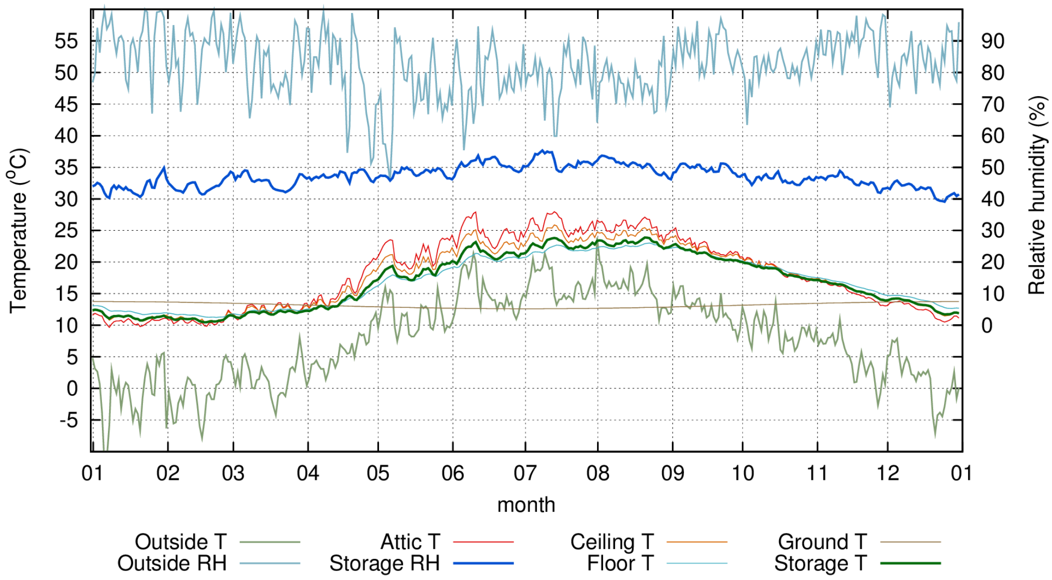

Figure 5: The indoor climate inside a store with a roof window. The RH is kept within 40% to 60% at all times. The RH is moderated not only by solar heating but by buffering by a lining of unfired clay brick. This computer simulation is based on the Ribe storage building and the Danish Reference Year for weather (details in the appendix).

Relative humidity buffering as a supplement to conservation heating

The relatively high temperature required to keep the RH down in summer accelerates degradation reactions. The temperature excess over ambient in summer can be minimised by relying on RH buffering to tide the store over the summer temperature theoretically required to keep the RH moderate. The store will be out of equilibrium with the water content of the outside air but will be buffered by the unfired clay wall cladding. In winter, the humidity buffering operates to increase the low RH which would theoretically result from the floor heating.

Evidence for the effectiveness of humidity buffering in museum stores has been presented in several publications [3,6-8]. Padfield and Jensen [9] have quantified the buffer performance of various materials and have proposed a method for predicting the buffer performance of buildings. Their analytical method has been applied to an experimental buffered room, without stored materials, to demonstrate the effectiveness of buffering even in stores without moisture-reactive artifacts.

The room has concrete walls, gypsum plastered and painted. It has two outer walls with a west facing window. The volume is 26 m^3 and the surface area of wall is 56 m^2. Only 7.5 m^2 of an internal corner of this wall is covered with unfired brick, 110 mm thick. The measured air exchange rate is 0.125 per hour.

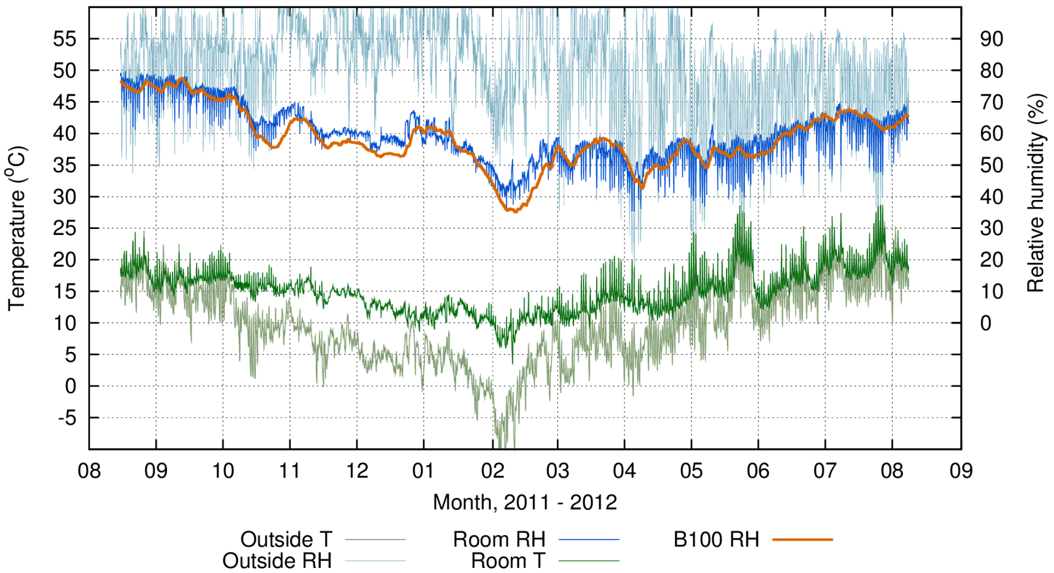

Figure 6: The measured course of the climate within a room partly lined with clay bricks. The smoother, orange trace is the RH predicted for the room, assuming a B–value 100 for the unfired clay brick. See Padfield and Jensen [9] for an explanation of the calculation.

In Fig. 6 the predicted course of the RH is derived from the *B–value* for unfired clay brick as defined and measured by Padfield and Jensen [9].

Briefly, the B–value is the volume in cubic metres of air whose RH will change equally to the change in equilibrium RH at the surface of a square metre of the material when the same amount of water vapour is added to the air as to the material. This apparently complicated definition of buffer capacity allows a simple approximate calculation of the stabilising effect of various wall covering materials, as well as of stored materials.

The smoothness of the predicted RH is due to using the long term B–value appropriate to a nearly airtight enclosure. Over shorter periods of fluctuation the B–value is smaller, because only the surface layer of the buffer is involved. In this particular room the absorbent walls do not calm the daily spikes in RH caused by sunlight, because the temperature of the wall surface is also buffered and is therefore more constant than the air temperature where the RH is measured in the centre of the room.

The stability of this empty room, imposed by a relatively small portion of the wall surface, shows that humidity buffering will greatly reduce the effect of variation in solar gain with changing weather. The simulation of the large store shown in Fig. 5 also includes humidity buffering, but through a more elaborate calculation.

Besides the excellent moisture-buffering capacity of clay, the material has a great potential of absorbing reactive compounds from the air, especially acid gases, and therefore acts as a pollution sink [5].

Conclusion

We have shown, through a combination of climate predicting programming and experience from actual buildings, that museum stores can be air conditioned completely passively, if a period of relatively high summer temperature is acceptable, or with only locally collected solar energy used to supply a mechanical dehumidifier if there is a need to keep the temperature low. In both models it is essential to keep the air exchange rate low and it is essential to use the earth under the building as a heat sink. Pollution from outside air is excluded; pollutants generated within the building can be absorbed from recirculated air, if necessary, or by a reactive wall lining.

Acknowledgements

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Appendix

Technical details of the simulations

Solar heating was simulated for a building similar in construction to that of the storage building for the Museums of South West Denmark, in Ribe. The simulation software was BSim, version 6,11,1,14, by the Danish Building Research Institute (SBI) at Aalborg University.
http://www.bsim.dk

For outdoor climate, the Danish Reference Year (DRY) was applied to the model, and the building was given the same geographical orientation as the real building. The gables were facing East - West. The roof had a 20°pitch. Solar panels or window were tilted towards the south.

Internal dimensions of the storage room: 41.73 m x 24.73 m x 6.48 m high.

Model construction:
Walls (from the inside): Unfired clay brick 110 mm; PVC vapour barrier 0.2 mm; Mineral wool thermal insulation 250 mm; Board 26 mm. Total thickness 386 mm. U-value 0.13 W/m^2K.
Ceiling: Concrete 100 mm. U-value 2.5 W/m^2K.
Floor: Concrete 200 mm laid directly on the ground; Soil 7800 mm. Total thickness of the ground element: 8000 mm. U-value (concrete floor) 1.3 W/m^2K. U-value (concrete and soil element) 0.25 W/m^2K.
Window: 80 m^2: Low-energy type glass in aluminium frame. U-value 0.56 W/m^2K.
Air exchange rate: 0.03 $hour^{-1}$.
The real building in Ribe has an inside lining of fired Moclay brick instead of unfired brick.

The temperature gradients shown in Fig. 2 are based on a heat transfer simulation by computer, using the Danish Reference Year for outdoor conditions. The simulation was made with Comsol Multiphysics (version 3.5a), using the same construction as the actual building in Ribe. In the real building in Ribe temperatures have been monitored inside and outside since 2008, both in the air and under ground to a depth of 2 m. These data were published by Ryhl-Svendsen et al [2]. The measurements show a higher indoor air temperature in winter than is predicted by the model (about 9 °C), and also the measured soil temperature at 2 m was higher (about 12 °C). These elevated temperatures are due to unintended heating of the storage room by the fan, dehumidifier and lighting. Besides this there may be a variation in climatic influence from year to year, which differs from that of the standardized (artificial) reference year.

Biographies

Morten Ryhl-Svendsen (1) is a senior scientist, Lars Aasbjerg Jensen (2) is a conservator, Poul Klenz Larsen (3) is a senior consultant, and Benny Bøhm (4) (retired 2011) was a climate consultant, all with the National Museum of Denmark, and with preventive conservation and energy efficient climate control for cultural heritage buildings as their main field of work. Tim Padfield (5) was formerly with the National Museum of Denmark. He is now a freelance consultant in preventive conservation, based in Devon UK.

Author e-mail:
1. morten.ryhl-svendsen@natmus.dk (author for correspondence)
2. lars.aasbjerg.jensen@natmus.dk
3. poul.klenz.larsen@natmus.dk
4. email as for (1)
5. tim@padfield.dk