Hygrothermal Performance Optimization of a Museum Storage Building

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ABSTRACT

For optimal longevity of the stored objects, museum storage buildings require a very stable interior climate, with only minimal and slow variations in temperature and relative humidity. Often extensive heating, ventilating, and air conditioning is installed to provide these stable indoor conditions. The resultant significant energy and maintenance costs are currently motivating a paradigm change: passive control, via the thermal and hygric inertia of the building, is gaining foothold in the museum conservation and building physical community.

In this paper we report a hygrothermal performance optimization of a museum storage building related to an existing storage in Vejle (Denmark). The current building design already incorporates passive control concepts: thermal inertia is provided by the thick walls, the ground floor, and its underlying soil volume, and hygric inertia is provided by the thick walls of light-weight concrete. The design promise was that after a few years of dehumidification, the moisture contained in the fresh constructions would be brought down to a level corresponding with the desired interior climate, after which the passive control would eliminate the need for dehumidification. Four years after completing the construction, however, continuous dehumidification is necessary to maintain acceptable humidity levels in the storage rooms. This paper presents an analysis of this contradiction and shows that such complete passive conditioning is an illusion. The general levels of humidity of the exterior environment are too high, which leads to unfavorable conditions for the interior environment. Continuous dehumidification is required, and a new concept for optimization of the building's thermal insulation and infiltration behavior in relation to the required dehumidification load is invented. The investigation shows that the impact of thermal improvements is minor, while any intervention in the airtightness has a considerable effect. The combination of the two brings the dehumidification needs down by 79%, with a minor price to be paid in the form of an increased potential for mechanical and chemical decay.

INTRODUCTION

Generally, the conservation of historic objects benefits from stable and low temperatures and relative humidities. Strong variations in relative humidity and temperature may lead to mechanical decay due to the related dimensional changes (Padfield 1998). High humidity levels may yield biological decay, since they encourage the activity of fungi and molds. Finally, high temperature levels may give chemical decay, as they advance chemical reactivity (Padfield 2005).

Commonly, extensive air conditioning is implemented to ensure this quality of the interior environment in museum storages and museum displays. That option, however, results in significant energy consumption, which is economically and ecologically not preferable (Padfield 2007; Padfield et al. 2007; Padfield 2008). In response, an alternative is currently being developed and promoted: passive conditioning (Christoffersen 1995; Padfield et al. 2007; Padfield 2008). In this approach, the application of high thermal insulation and high thermal and hygric inertia should allow to sufficiently stabilize the interior climate with no or minimal need for mechanical air conditioning. This concept historically dates back to castles and churches, original safe keepers of art, where heavy

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constructions with high hygrothermal inertia lead to a slow fluctuation of temperature and relative humidity (Svendsen et al. 2003).

Problem Statement

In 2003, 16 regional museums in Western Denmark decided to construct a shared storage facility in Vejle (Denmark). To reduce the initial and running costs of the storage, modern industrial building techniques were to be combined with passive conditioning of the interior climate. The desired interior climate would allow slow variations between 12°C and 14°C and 45% and 60% RH. Therefore, a relatively airtight building was built, with strongly insulated building parts and high hygrothermal inertia. Hygric inertia is provided by 24 cm interior walls and 24 cm interior leafs of external walls in light-weight concrete. These also provide thermal inertia to which the uninsulated floor equally contributes.

Christoffersen and Kristensen (2004) state that "use of the building physical properties of the construction elements allows the building to control its interior climate without use of mechanical conditioning." This statement is complemented by "the moisture contained in the fresh constructions is to be brought down to a level corresponding with the desired interior climate, which requires that the passive conditioning at the start is supported by dehumidification. The heavy constructions generally require a few years of drying."

Four years after completing the construction, however, continuous dehumidification is necessary to maintain acceptable humidity levels in the storage rooms. This paper presents an analysis of this contradiction. It is shown that such complete passive conditioning is an illusion. In a further development, the current design of the building is optimized towards minimal energy use for dehumidification.

Building

The complete museum storage consists of four halls separated by a corridor (two small halls, two large halls), the conservation center, and shared facilities (see Figure 1). In the museum storage, 75% of the area of the four halls contains a mezzanine construction with a floor of industrial grates. The four halls were divided according to requirement of the collections into areas with different climates (Knudsen and Rasmussen 2005):

- Halls A, C, and D: 4122 m^2 area with basic climate for wooden objects, paintings, etc.; 45%–60% RH, with a small dehumidifier for high peaks of humidity); 6°C–17°C.
- Hall B: 658 m^2 area for archaeological finds and metals; 40% RH, with a small dehumidifier and supportive heating; 10°C–17°C.

Since lighting emits ultraviolet light, which in the long run damages many of the objects and consumes energy, infra-

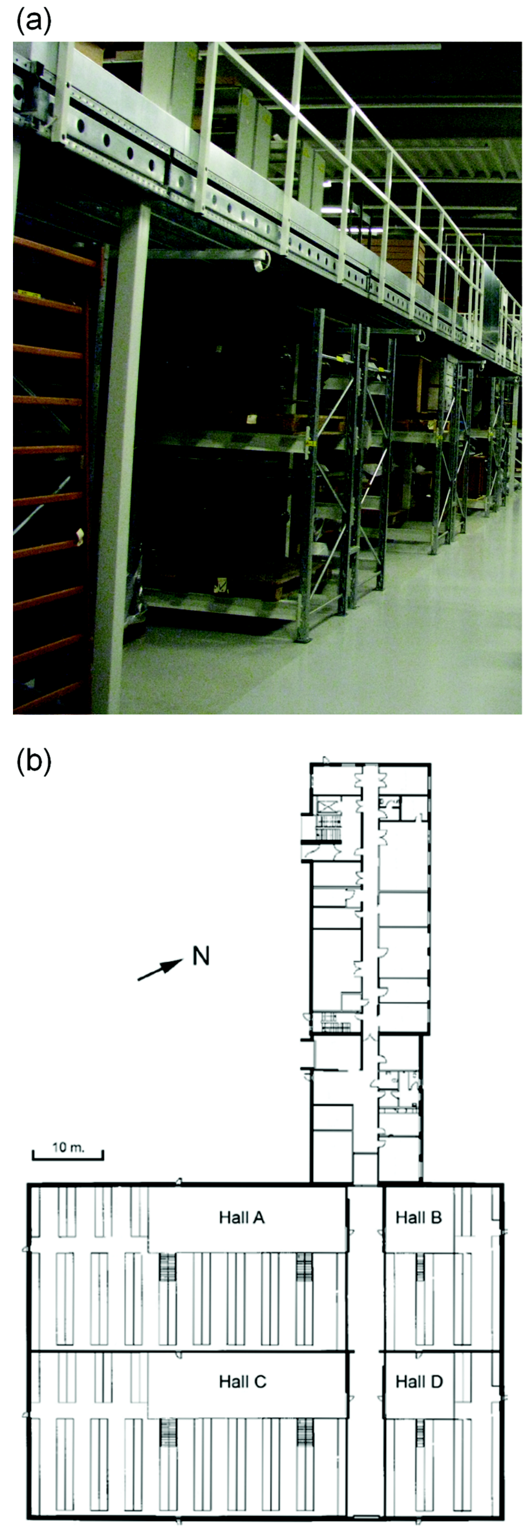

Figure 1 *(Top) a picture of the interior of the museum storage and (bottom) a plan of the complete museum storage: four storage halls at the bottom, the conservation center at the top, and shared facilities in the middle. (Drawing courtesy of Knudsen.)*

red detectors have been installed in order to ensure that the light only activates when someone is in the area. Furthermore, the light level is only 70 lux in the working area; other parts of the hall are not illuminated.

The floor has been painted with epoxy to protect against mechanical wear and keep it clean. This helps pest monitoring, which is an important issue for the storage. However, the epoxy paint reduces the hygrothermal conditions for the floor. The wall has been painted with white paint of high permeability. The light colors reduce the necessary light effect in the storage. The philosophy behind the light painting is to encourage people to show respect for the storage and to take responsibility for keeping it clean.

The building is based on passive climate control concepts: a concrete building with exterior insulation and no traditional insulation in the floors. The construction is listed from interior to exterior (Figure 2) (Knudsen and Rasmussen 2005; Rasmussen 2007):

- Walls—cement-based white paint of high permeability, 240 mm lightweight concrete (1600 kg/m^3), 240 mm insulation, corrugated steel plating protection.
- Roof—precast concrete TT-beams connected by corrugated metal sheets, 300 mm isolation, double-felted asphalt roof.
- Floor—grey water-based epoxy paint (to protect it against mechanical wear and the formation of dust), 100 mm concrete, 150 mm light expanded clay aggregate (Leca), waterproof membrane.

METHODOLOGY OF INVESTIGATION

The reported investigation has two aims: (1) to clarify the contradiction between the hygrothermal behavior of the storage, as promised by the design and as observed in reality, and (2) to further optimize the building design in relation to the required dehumidification. Both aims are accomplished via hygrothermal building simulation using BSim, developed by the Danish Building Research Institute (SBi 2005). The program allows calculation of the interior climate of the storage building, with consideration of the interaction with the heat and moisture transfer in the building envelope. Toward that aim, a one-node model for the interior environment is coupled to a one-dimensional control-volume-based model for the components.

BSim Modeling

Model Geometry. Despite the interior walls and the two climate zones in the real building, the building is modeled as a single zone. It is assumed that this simplification does not affect the overall observations from the numerical analysis. Moreover, while some doors (main entrances and emergency exits) and skylights (for smoke evacuation purposes, covered to avoid solar exposure) form part of the building envelope, it is equally assumed that their effect on the hygrothermal behavior of the storage building is minimal. The interior walls, on the other hand, are maintained in the model, as they provide a significant part of the interior thermal inertia. Finally, only the conservation halls themselves are modeled: the shared facilities neighboring the building are omitted. The model for the building thus boils down to a simple rectangular box with interior dimensions of 67.2 × 47.3 × 6.1 m. These result in an interior floor area of 3177 m^2 and an interior volume of 19,400 m^3.

Figure 2 Picture of the museum storage from outside.

The exterior walls are modeled with the following material layers (interior to exterior): vapor-open paint (vapor diffusion thickness of 1m), 240 mm lightweight concrete (1200 kg/m^3), 200 mm low-density mineral wool (32 kg/m^3) and 40 mm high-density mineral wool (150 kg/m^3), and metal sheathing. The interior walls consist of the 240 mm lightweight concrete (1200 m^3) painted at both sides. The largest section of the roof, 70% of the surface area, is composed of 2 mm metal sheathing, 300 mm low-density mineral wool insulation (32 kg/m^3), and double-felted asphalt roof. In the other part, the 2 mm metal sheathing is replaced by 300 mm of heavy-weight concrete (2300 kg/m^3) representing the actual TT-beams supporting the roof.

The basic floor construction consists of 100 mm heavyweight concrete (2300 kg/m^3), 150 mm leca pellets (325 kg/m^3). However, the three-dimensional transport and storage of heat in the soil volume below the building significantly affects the thermal inertia available to the interior climate. The one-dimensional modeling restriction of BSim does not allow easy implementation of such three-dimensional behavior. To resolve this issue, a specific ground heat transfer methodology is developed in the section "HEAT2 Modeling." More details on the floor modeling can be found there.

Air Infiltration. No specific ventilation with outdoor air is implemented in the real building nor, therefore, in the numerical model. Infiltration of outdoor air, through air leaks in the building envelope, is however unavoidable. A blower-door test performed on the actual building reveals an air change rate of 0.65/h at 50 Pa pressure difference. Based on Sherman (1987), this translates to an likely air change rate of 0.04/h. As Sherman developed his correlations mainly for single-family houses, this final value may be inaccurate for the large storage building considered here. Validation of the model, however, indicates that this is an acceptable value. This value is, moreover, in agreement with the original design value implemented in the original design (Petersen 2002), which makes confrontation far more straightforward.

Interior and Exterior. The main interior heat gains stem from people working in the storage areas and the lighting that is at such moments required. It is assumed that on weekdays the average human presence corresponds to 8 person hours. The light level required for work in the storage is 200 lux. If provided by low-energy fluorescence lights, these yield interior heat gains at 5 W/m^2 (DANVAK 2006). Accounting for the limited human presence and sectioning of the lights transforms this into 19 kWh each weekday. This is implemented as an interior heat gain of 2.4 kW during 8 hours for every working day.

For the exterior climate, the Design Reference Year (DRY) data for Denmark are used. The Danish climate has an average temperature of 7.8°C and 83% RH.

HEAT2 Modeling

A very important aspect in the BSim model is the thermal interaction between the interior atmosphere and the volume of soil below the building. This is essentially a three-dimensional (3D) interaction (Claesson and Hagentoft 1991), defying BSim's one-dimensional (1D) modeling approach. Thus a methodology is required to develop an adequate equivalent 1D description of this 3D process. The 1D model will consist of the concrete and leca layers finalized with a layer of soil. Interior boundary conditions are implemented on the surface of the concrete, while exterior boundary conditions are applied on the opposite surface of the soil layer. The methodology outlined below allows quantifying the necessary thickness of the soil layer in the 1D model to obtain a thermal interaction equivalent to the original 3D process.

Two-Dimensional. We need to assess the response of a half-infinite soil volume to excitation with a variable interior temperature over a rectangular section of the surface, and with a variable exterior temperature over the remaining part of the surface. The thermal influences of the building on the soil domain are fortunately limited in space, and EN ISO 13370 (EN 2007) formulates guidelines on how to limit the simulation domain to a limited 3D volume. Anderson (1991) establishes that the 3D heat exchange can be adequately described with a 2D geometry: with a length equal to the perimeter P of the building and a width equal to the equivalent width B' defined by Anderson (1991):

$$B' = \frac{A}{P/2} \tag{1}$$

where

B' = equivalent width, m

A = surface area building, m^2

P = perimeter building, m

In essence, this requires the calculation of the 2D heat loss from a structure with half the characteristic width $B'/2$ (as symmetry can be applied), which afterwards is to be multiplied with the perimeter P of the building to obtain the total heat exchange between building and soil.

Such 2D simulations form the start of the methodology, and these are performed with HEAT2, providing numerical solutions for multidimensional heat transfer. Three different simulations are run:

- Steady-state, interior temperature: 1°C; exterior temperature: 0°C
- Transient, interior temperature: 0°C; exterior temperature: 1°C harmonic variation around 0°C with a period of 1 year; phase angle determined from Danish DRY
- Transient, interior temperature: 1°C harmonic variation around 0°C with a period of 1 year; interior temperature: 0°C; phase angle determined from measured interior temperatures;

All actual excitations can be composed from these three fundamental regimes via the principle of superposition of linear solutions.

One-Dimensional. The soil layer thickness in the equivalent 1D floor structure is determined from imposing an equality of the steady-state heat flows of the 2D and 1D case. For example, for our building with dimensions 68.0 × 48.3 m, an equivalent 1D soil layer thickness of 11.8 m is obtained; the global thermal resistance of the soil domain is thus equivalent to a soil layer of 11.8 m. However, while agreement of the average heat flows is ensured, this does not necessarily guarantee the equivalency of the transient aspects of the thermal interaction between building and soil. Such lack of equivalency is illustrated in Figure 3, which compares the three simulation results (1 steady-state, 2 transient) for the 2D and the 1D models. The average heat flows are of course the same, while small deviations are noted for the responses to the interior temperature variation: there is a 4% deviation at the heat flow peaks. However, the 2D and 1D responses to the exterior temperature variation are drastically different, both in amplitude and in phase angle. Thus, the simple translation of the original 3D process to a single 1D equivalent does not yield satisfactory results. In the 2D model, there is only a small phase difference between the exterior temperature variation and the corresponding heat flows near the perimeter of the building where the heat flows are relatively large and dominate the overall heat flow. The 11.8 m soil layer in the 1D model can apparently not capture this short-term influence. Figure 3 shows that the exterior temperature variation yields the smallest response, rendering it perhaps insignificant. Note, however, that these are responses to a 1°C excitation, requiring multiplication with the actual temperature difference or amplitude. As the exterior temperature amplitude usually exceeds the interior variation amplitude and the average interior-exterior temperature difference, a sufficiently accurate 1D response is still necessary.

To improve on that, the original width $B'/2$, 14.1 m for the building considered, is discretized into five separate zones, with respective widths of 1, 1, 1, 2, and 9.1 m (starting from

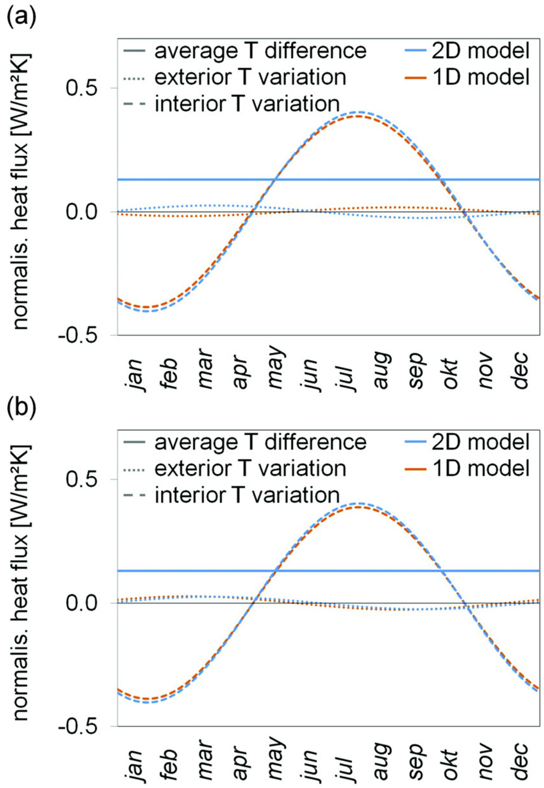

Figure 3 *Confrontation of thermal response of (a) original 2D model and equivalent 1D model and (b) original 2D model and five-zone-composite equivalent 1D model.*

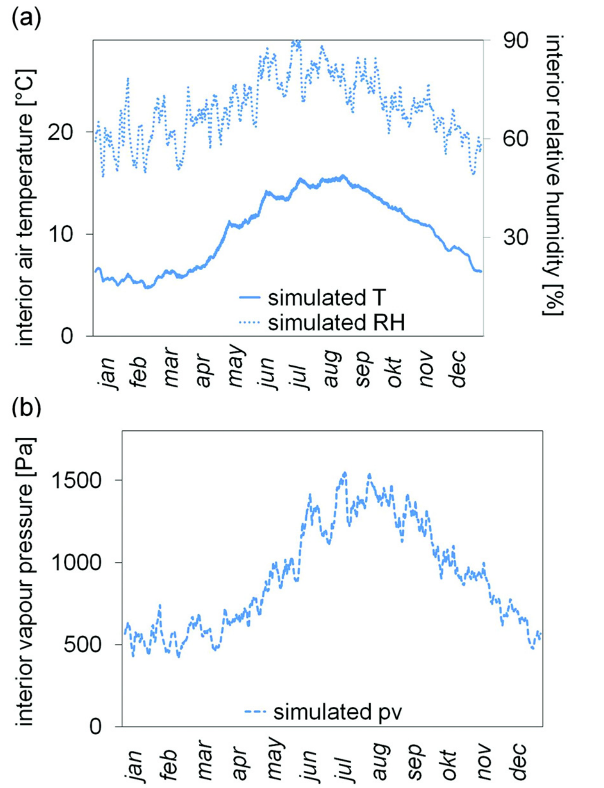

Figure 4 *Hourly values for (a) interior temperature and relative humidity and (b) vapor pressure.*

the building perimeter). In the 2D simulations, the heat flows through these zones for the floor are monitored separately and then used to define five equivalent 1D models, each with a specific equivalent soil thickness. This discretized approach results in soil thicknesses ranging from 0.9 m (floor zone nearest to perimeter) to 19.7 m (floor zone furthest from perimeter). It can be seen in Figure 3 that the original 2D results and the composed 1D results compare much better concerning their responses to the exterior temperature variation. The discretized approach clearly allows the 1D model to mimic the small phase difference for the floor zone near the perimeter, as well as the larger phase difference for the central floor zone. Thus, in the BSim model, the floor is modeled with five proportionally sized floor zones, each with their particular equivalent soil layer thickness.

ANALYSIS OF THE CURRENT SITUATION

Presentation of the Results

The developed building simulation model allows quantifying the expected variations in indoor temperature and humidity levels for the current situation. These can be found in Figure 4, which shows hourly values for the interior temperature, relative humidity, and vapor pressure. From Figure 4, it can qualitatively be observed that the high hygrothermal inertia of the building yields a fairly stable climate, at least for daily variations. Quantitatively, this is assessed with the deviation between each hourly value and the average of a twenty-four-hour interval centered round that value:

$$DA_T = \sqrt{\left(T_i - \sum_{j=i-11}^{i+12} T_j/24\right)^2} \qquad (2)$$

where

DA_T = daily amplitude, °C

T_i = hourly value of T at hour i, °C

For the current building, the 8760 hourly DA_T averaged to 0.063°C, with a maximum value of 0.201 °C. This implies that the daily variation is 0.13°C on average, and the strongest daily variation is limited to 0.4°C. Daily variations in the relative humidity can be evaluated similarly, averaging to 0.94%, with a maximum of 5.2%. A comparison of the variations in temperature, vapor pressure, and relative humidity (see Figure 4) indicates that the variations in relative humidity are primarily a consequence of variations in vapor pressure rather than temperature. Thus, the daily variations of the interior climate are minimal. For that reason, and as our interest is primarily in the overall performance, all results are from here on represented with monthly averages.

The monthly averaged interior temperatures and relative humidities are shown in Figure 5. From Figures 4 and 5 it is obvious that the original requirements for the interior climate are not met: the temperature varies between 5.2°C and 15.3°C, while the relative humidity varies between 59% and 82%. This is clearly not within the limits of the original performance requirements. The effects of the temperature variation on the deterioration of the stored collection items, however, are most probably very limited, due to the slow rate of the variations (Padfield 2008). The elevated humidity levels, on the other hand, are clearly unacceptable in relation to the conservation aims of the storage center. If correct, these high humidity levels explain the dehumidification needs in the actual building.

Validation of the Developed Model

To confirm the reliability of the developed model and its results, the simulated interior temperatures are compared to the interior temperatures measured in the building during the year 2007. Temperatures have been continuously monitored since the erection of the building, resulting in an extensive record of ten-minute-spaced values for the interior air temperature in the four halls. Similar measurements are available for

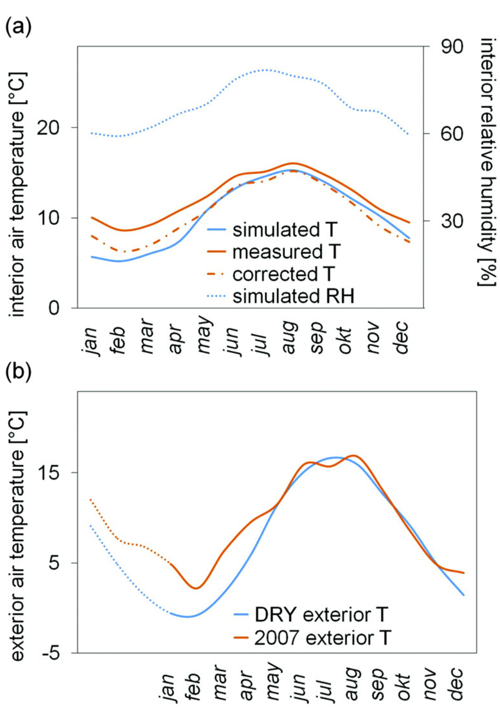

Figure 5 *Simulated and measured (a) interior temperatures and (b) exterior temperatures.*

the relative humidity, but comparison with these is not rewarding: in the real building, dehumidification takes place, while the simulations do not incorporate this measure.

Figure 5 depicts the confrontation between simulated and measured interior temperatures. It is obvious that the agreement between both is far from satisfactory. It should, however, be noted (see Figure 5, right) that the exterior temperature during 2007 does not correspond to the DRY data employed in the simulations; average and amplitude of the simulated exterior temperature are significantly higher than those of the measured exterior temperature. A correction is thus due. In both measurement and simulation, the interior temperature is determined by a balance of interior heat gains and heat losses to the exterior. As the heat gain can be considered evenly distributed over the entire year, the interior temperature's average and amplitude are a direct response to the average and amplitude of the exterior temperature: higher values of the latter give higher values of the former. This principle can be used to correct the measured interior temperature for a virtual forcing by the DRY values for the exterior climate. The result of this correction is equally shown in Figure 5. While the correction is based on the exterior air temperatures only, excluding all other atmospheric influences, it is concluded that good agreement is obtained between measurements and simulations. The correspondence is not perfect for the first few months of 2007, but this is attributed to the fact that the year 2006 was even warmer than 2007. The response during these first few months of 2007 is partially governed by these 2006 conditions, hence the underestimation by the simulations. This effect can not, however, be easily inserted in the correction. In general, the reliability of the developed model is assumed confirmed.

Confrontation and Conclusion

Figure 6 brings the originally designed interior temperatures and relative humidities and their newly simulated values together. It is obvious that serious differences exist: the designed temperatures are far higher, while the designed relative humidities are far lower. The vapor pressure agreement indicates that the relative humidity differences are caused by the temperature differences.

This leaves only one possible conclusion. Whereas the original design was labeled a primarily passive solution for the conditioning of the storage center, it is obvious from Figure 6 that conservation heating is applied in the design to maintain acceptable interior humidity levels. This does indeed become clear from a technical design note (Petersen 2002), but this active measure is not mentioned in Christoffersen and Kristensen (2004). The conservation heating is, moreover, not implemented in the actual building, which explains its continuous need for dehumidification.

In the end, the exterior climate of Denmark makes it impossible for full passive conditioning to yield acceptable conservation conditions. Without any interior heat or moisture gains, the yearly averaged temperature and vapor pressure equilibrates with their exterior counterparts. From the DRY for Denmark, this translates to 7.8°C and 930 Pa. The resulting yearly averaged interior relative humidity thus becomes 88%. Interior heat gains and solar gains at the building surfaces raise the actual temperature level to 10.2°C, which lowers the relative humidity to 75%. This general level of interior humidity can also be observed in Figure 6. While the strong hygrothermal inertia of the building may be able to dampen the variations in interior temperature and humidity, the inertia can not affect the average temperature and humidity. Full passive conditioning must be considered an illusion, notwithstanding the positive assessments voiced by Christoffersen (1995) and Christoffersen and Kristensen (2004). This reflection confirms the conclusion of Padfield et al. (2007) who state that conservation heating or dehumidification are a must to ensure acceptable conservation conditions.

REDUCTION OF DEHUMIDIFICATION

While the original design opts for conservation heating to lower humidity levels, the actual building makes use of dehumidification (via absorption drying). This choice is based on economic as well as conservation reasons. Rhyl-Svendsen et al. (2009) compare the energy needs for conservation heating and dehumidification of a conservation storage building very similar to the one investigated here. They conclude that for low air change rates—below 6 times per day—dehumidification is

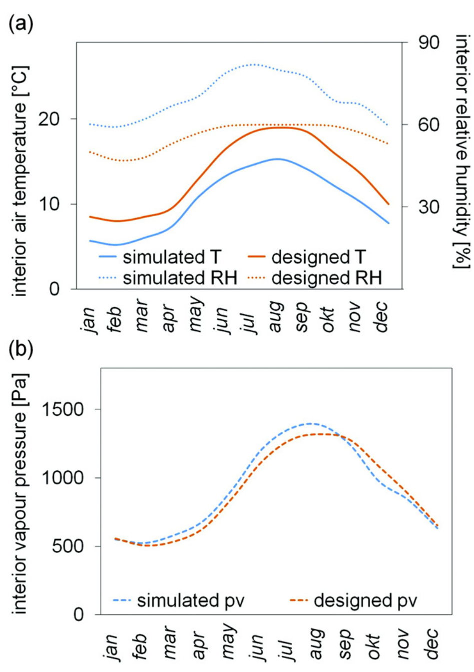

Figure 6 *Confrontation of originally designed and newly simulated (a) interior temperatures and relative humidities and (b) vapor pressures.*

the cheaper solution. Moreover, conservation heating increases the general temperature level, which negatively influences the chemical deterioration of the stored objects: the chemical reaction rate is proportional to the temperature. Hence, higher temperatures accelerate the chemical decay of stored objects. Dehumidification, on the other hand, allows for lower interior temperature levels, improving the potential conservation.

To maintain 50% interior relative humidity in the current building year round, permanent dehumidification is required. A mass balance of human vapor production and vapor transfer by air infiltration and exfiltration allows quantifying the expected needs for dehumidification. For the building in its current state, this amounts to 14710 liters per year. As indicated before, this dehumidification forms the main share of the building's energy consumption. The dehumidification needs peaks in summer, due to the high interior temperatures and humidities, while it is relatively lower in winter.

Thermal Insulation and Airtightness

In what follows, various design changes are examined with respect to their effect on the required dehumidification, focusing on improvements for thermal insulation and airtightness. The potential of thermal improvement can be illustrated from the effect of changes in the current temperature average and amplitude. A 1°C rise in the yearly average temperature decreases the dehumidification load by 14%, while a 1°C fall raises it by 13%. Increasing/decreasing the yearly amplitude by 50% reduces/raises the dehumidification by 6% and 4%, respectively: higher temperatures during the summer lessen the peak dehumidification, dominant in the overall load.

Eight different cases are studied: the original construction, six separate modifications of airtightness and thermal insulation, and a final combination of these, representing the new possible design. The eight cases are shown in Table 1.

All simulation results are collected in Figure 7. The main simulation results are the interior temperatures; these are quantified with their yearly average and amplitude (half of the difference between the highest and lowest monthly average temperature) and their average daily amplitude, as calculated with Equation 2. The latter is a measure for potential mechanical deterioration, as the daily temperature variation controls the short-term expansion and shrinking of objects. Relative humidity variations have a similar impact via hygric strains and stresses, but these are avoided by the dehumidification producing a stable relative humidity of about 50%. This level of relative humidity moreover prevents biological deterioration by minimizing the activity of fungi and molds. Chemical deterioration refers to the decay caused by chemical reactions inside the objects, for example the hydrolysis of polymers in paper. At constant relative humidity, the reaction rate is affected by the temperature via the Arrhenius equation. For the quantification of chemical deterioration, a virtual hydrolysis reaction is presumed, with 100 kJ/mol of activation energy and a reference reaction rate of 1°C at 20°C (Rhyl-Svendsen et al.

Table 1. Overview of Different Designs for the Storage Building

Case	Construction
1	Original building: 24 cm mineral wool wall insulation, 30 cm mineral wool roof insulation, 15 cm leca floor insulation, 0.04 ach
2	50 cm mineral wool wall insulation
3	15 cm PUR foam floor insulation
4	50 cm mineral wool roof insulation
5	20 cm mineral wool roof insulation
6	10 cm mineral wool roof insulation
7	0.01 ach
8	50 cm wall, 15 cm floor, 20 cm roof, 0.01 ach

2009). The relation between reaction rate and temperature can then be quantified as follows:

$$RR = Ae^{\frac{-E_a}{RT}} \tag{3}$$

where

RR = reaction rate, dimensionless

A = reaction rate constant, $7.02 \cdot 10^{17}$

E_a = reaction's activation energy, 100 kJ/mol

R = universal gas constant, 8.31 J/mol·K

T = reaction's temperature, K

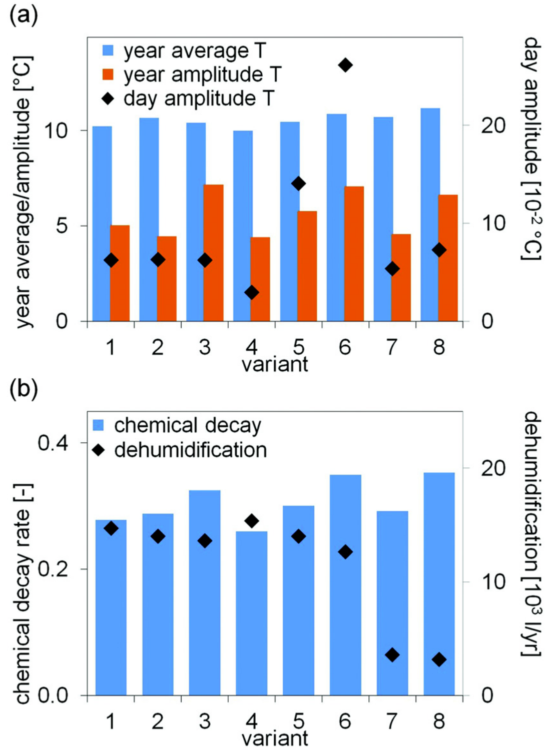

Figure 7 *Simulation results (a) yearly average, yearly amplitude, and daily amplitude of interior temperatures and (b) yearly average chemical decay potential and yearly dehumidification load.*

Equation 3 allows conversion of all hourly temperature values to a virtual hydrolysis reaction rate. The yearly averaged value for all 8760 reaction rates is assumed a measure for the potential chemical deterioration. Finally, the yearly dehumidification load to maintain 50% RH year round is given in Figure 7.

From Figure 7, many observations can be made. Increasing the insulation thickness of the storage's walls to 50 cm (variant 2) globally decreases the transmission losses. This increases the temperature's yearly average and amplitude and decreases its daily amplitude. In response, the yearly dehumidification load decreases by 4.8% and the chemical decay potential increases by 3.6%. Replacing the 15 cm leca layer in the floor with polyurethane foam insulation (variant 3) mainly has an effect on the yearly amplitude. The dimensions of the building make the soil volume under the building already fairly insulating: the insulation does not change its U-factor significantly, thus the limited effect on the yearly average. The insulation doesn't affect the short-term inertia of the floor, hence the restricted influence on the daily amplitude. The insulation, however, lessens its long-term inertia, which is reflected by the larger yearly amplitude. This larger amplitude results in a lower dehumidification load but a higher chemical decay. Note, however, that both effects are minimal. Increasing the roof insulation thickness to 50 cm (variant 4) results in a decrease in the yearly average, opposite the two previous variants. This may be explained by the solar radiation on the roof's surface, which obviously leads to a sol-air temperature above the interior temperature. This suggests that the roof actually delivers a heat gain to the building. This is confirmed by lowering the insulation thickness in the roof to 20 cm and 10 cm (variants 5 and 6, respectively), which pushes up the yearly averages of the interior temperature. However, decreasing the roof insulation to 10 cm quadruples the daily amplitude to 0.26°C. The latter is a yearly average value, the maximum for variant 6 is 0.87°C (while the original construction has a maximum daily amplitude of 0.20°C). The influence of the insulation thickness in the roof on the temperatures translates to the expected effects on the dehumidification load and chemical decay potential.

In general, the influence of the purely thermal measures is limited; the dehumidification loads can be brought down by 5% to 10% at most. This reduction often comes at the expense of a higher mechanical decay potential through higher daily temperature amplitudes, or a higher chemical decay potential through the generally more elevated temperatures. The only efficient measure is a reduction of the infiltration rate (variant

7). While the effects on the overall thermal behavior and the potential mechanical and chemical decay remain limited, the dehumidification load is greatly reduced. The original building with 0.04 ach required 14,710 L/y in dehumidification, while the 0.01 ach necessitates 3560 L/yr. The infiltration of exterior air is indeed the primary moisture source for the interior climate; any reduction of the air change rate evidently leads to a reduction of the required dehumidification.

Finally, the combination of 0.01 ach, 50 cm wall insulation, 15 cm floor insulation, and 20 cm roof insulation (variant 8) further reduces this to 3140 L/y. Such a solution does slightly raise the daily temperature amplitude (by 17% in comparison to the original) and the chemical decay potential (by 27% in comparison to the original). But in general it is assumed that these changes are minor and are compensated by the 79% reduction of the original yearly dehumidification load.

CONCLUSION

In traditional museums, objects are treated in accordance with the highest standards in order to keep them under good conditions. The consequences of this are expensive operating costs. In order to solve this challenge it has been very important to develop an economical and good answer that offers an alternative and realistic solution. The concept is called *passive climatization* and functions by creating a stable indoor climate by using the thermal inertia provided by the thick walls, the ground floor, the underlying soil volume, and hygric inertia provided by the thick walls of light-weight concrete.

In this paper we have studied a museum storage building, which has been built according to the passive control concepts. The original design was labeled a primarily passive solution for the conditioning of the museum storage building and was based on the principle that after a period of few years of dehumidification the moisture in the constructions would be dried out. After this, the thermal and hygric inertia in the museum storage would be enough in order to avoid further dehumidification. Measurement from the building shows after four years that continuous dehumidification is necessary in order to keep an acceptable humidity level. The calculation shows in the end that the exterior climate of Denmark makes it impossible for full passive conditioning to provide the necessary RH between 45% and 60%, which is the acceptable level for conservation conditions.

Notwithstanding the original design promises, the previous results demonstrated that a fully passive approach for conditioning of museum storage center is an illusion. The general levels of humidity of the exterior environment are too high, which leads to unfavorable conditions for the interior environment. Continuous dehumidification is, therefore, required, and this paper presented the optimization of the building's thermal insulation and infiltration behavior in relation to the required dehumidification load. It has been shown that the impact of thermal improvements is minor, while any intervention in the airtightness has a considerable effect. The combination of the two reduces the dehumidification needs by 79%, with a minor price to be paid in the form of an increased potential for mechanical and chemical decay. Using this concept, the variation in the relative humidity will be very limited during the day. This makes it possible to use night dehumidification limited to only six hours per day. This will allows the possibility of using cheap night electric tariff and electricity from the general overproduction of wind-power energy in Denmark at night. Together, these will make the museum storage building nearly CO_2 neutral.

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