HYGROTHERMAL OPTIMISATION OF MUSEUM STORAGE SPACES

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ABSTRACT (200 words max)

Despite the large economic and ecologic costs, museum storage spaces are often equipped with extensive air conditioning, to provide the desired stable interior climate. The new “passive conditioning” paradigm aims at resolving these costs: a high-hygrothermal-inertia building with a high-hygrothermal-resistance envelope is to satisfactorily stabilise that interior climate, with no need for mechanical air conditioning hence.

This paper first studies the reliability of full passive conditioning for museum storage spaces. It is shown to be an illusion, since it usually results in excessive interior humidities. Auxiliary dehumidification is thus required to provide good conservation conditions, and it is secondly investigated how the dehumidification load can be diminished. The study reveals the crucial impact of air tightness, while thermal insulation only has a minor influence.

To further reduce the economic and ecologic cost of conditioning, the paper finally assesses “concentrated dehumidification”: dehumidification during a part of the day only, while leaving the humidity free-running during the rest of the day. It is established that the hygric inertia of the interior air, building walls and stored objects keeps the fluctuations of the interior relative humidities to a minimum when considering adequately air tight museum storage spaces.

KEYWORDS

museum storage space, air conditioning, conservation conditions, dehumidification, inertia, moisture buffering

HIGHLIGHTS

- museum storage spaces require stable climates for optimal conservation of objects
- “passive conditioning” aims at reducing the connected economic and ecologic costs
- full passive conditioning of museum storages does give excessive humidities though
- air tightness, and not thermal insulation, has largest impact on dehumidification load
- concentrated dehumidification can additionally be applied, in air tight storage spaces

1. INTRODUCTION

Relative humidity and temperature play a decisive role in the conservation of historic objects [1–5]. Medium and stable relative humidities and low and stable temperatures are generally put forward as the ideal conservation conditions: high humidity levels promote pest development and mould formation, while low humidity levels provoke brittle failure of mineral and organic materials; high temperatures intensify chemical and biological reactions, and thus the natural deterioration of materials; strong fluctuations in relative humidity and temperature finally yield mechanical decay, due to the related dimensional changes [1]. It should be kept in mind though that there is ample discussion still on the levels and variations of relative humidity and temperature that produce tolerable change versus intolerable damage [1].

Nonetheless, many conservation standards now rigidly prescribe the preferred levels and allowed variations of the relative humidities and temperatures in museal storage spaces [1–5]. British Standard 5454 for example, on the proper conservation of archival documents, stipulates fixed relative humidity and temperature set-points (at a value between 45-60 %, 13-16 °C respectively) and minimal tolerances around these set-points (5 %, 1 °C respectively). It should be kept in mind however that many of the prescribed values are determined more by the practicality of air-conditioning-based interior climate control rather than by knowledge on hygrothermally induced physical damage mechanisms [5]. Even so, these prescriptions are now widely accepted and applied when conditioning museum storage spaces [6–10].

Usually extensive air conditioning is implemented to provide such strict control of the interior environment. That does result in a substantial energy consumption though, which is economically and ecologically inopportune, even despite efforts in the direction of 'low-energy museal spaces' [11–14]. As an alternative the 'passive conditioning' concept is currently being developed and promoted [15–17]: a storage with a high thermal and hygric inertia enclosed by an envelope with high thermal and hygric resistance should sufficiently stabilise the interior climate, with resultantly (virtually) no need for mechanical air conditioning. The passive conditioning concept connects to historical castles and churches – the earliest safe keepers of art –, in which bulky constructions dampen the temperature and relative humidity fluctuations [18]. The dependability of passively conditioned storage spaces has only been established though for applications where some indirect heating was available, or where particular ventilation strategies were applied [16–18].

This paper hence first aims at analysing the dependability of full passive conditioning for museum storage spaces. The analysis will demonstrate that this approach results in excessive interior humidities, and accordingly that passive conditioning is an illusion for many common climates. Instead, conservation heating or auxiliary dehumidification are necessary to maintain acceptable relative humidities in museum storage spaces. Secondly then, the paper investigates how the necessary conditioning of the storage space can be minimised. Counter to the reductions of the transmission and ventilation losses common for residential buildings, the investigation will show the minimal impact of these thermal measures on the dehumidification load, the key factor in the conditioning need. Instead, air tightness and concentrated dehumidification are put forward as the viable solutions for decreasing the energy consumption for the air conditioning of museum storage spaces, wherein concentrated dehumidification opens the door to air drying based on renewable sources.

2. HYGROTHERMAL NUMERICAL MODELLING

This study aims at quantifying yearly and daily variations of temperature and relative humidity in 'passively conditioned' museum storage spaces through numerical modelling. The use of heat and moisture simulation for hygrothermal performance assessment of buildings is at present well established [19], and recent applications to museal environments can be found in [12,20-21]. The specific application to passively conditioned museum storage spaces, as well as the combination of modelling approaches needed to that aim, has however not been presented earlier. In a first section, on passive conditioning and dehumidification reduction, the focus goes to the yearly thermal climate in storage spaces with supplementary attention

for the related hygric climate. To that aim an existing hygrothermal building simulation package is applied, enriched with a specific model for ground heat transfer though. In the second section on concentrated dehumidification, the emphasis lies on the daily hygric climate in storage spaces. For that goal transient vapour balances for interior air, building walls and stored objects are formulated analytically and solved numerically.

2.1 Specific calculation object

The study here is exemplified with an existing museum storage space, located in Vejle (Denmark). While all quantitative outcomes thus depend on this particular building, the qualitative conclusions are valid for general museum storage spaces. In 2003, 16 regional museums in Western Denmark decided to construct a common storage space. To reduce their initial and running expenses, industrial building techniques were merged with passive conditioning concepts. A relatively air-tight storage building was constructed, with strongly insulated building parts and large hygrothermal inertia: thermal inertia stems from the thick interior and exterior walls, as well as from the floor slab and the underlying soil volume; hygric inertia comes from the same interior and exterior walls of lightweight concrete [22-23]. The Vejle storage space consists of four different halls: two larger halls A and D, two smaller halls B and C, separated by a central corridor, see Figure **Error! Reference source not found.** For three quarters of the floor area a mezzanine with metal grate floors is provided. The halls are divided into two particular climates, according to the different requirements for the different collections [22-23]:

- A, C, D: 4122 m², 45-60 % RH, 6-17 °C (*wooden objects, paintings, etc*);
- B: 658 m², 40 % RH, 10-17 °C (*archaeological finds and metals*);

Despite the interior separating walls and the different two climate zones in the actual storage, the building is modelled as a single thermal and hygric zone for both the yearly hygrothermal climate and the daily hygric climate modelling. Furthermore, while doors (hall entrances and emergency exits) and skylights (for smoke evacuation purposes; covered to reduce radiation exposure) are part of the building envelope, these are not incorporated in the building model. Moreover, even though supporting facilities neighbour the storage space, these are similarly not included in the building model. It is assumed that these three simplifications only have a limited impact the hygrothermal behaviour of the storage space. The building model thus essentially boils down to a rectangular box with interior dimensions 67.2 x 47.3 x 6.1 m (interior floor area: 3177 m², interior volume: 19400 m³). All interior walls are maintained in the building model though, since they provide a substantial part of the thermal and hygric inertia.

In the yearly hygrothermal model, the exterior walls are modelled with the following materials (interior to exterior): cement-based paint (s_d -value: 1 m), 240 mm lightweight concrete (1200 kg/m³), 200 mm low-density mineral wool (32 kg/m³) + 40 mm high-density mineral wool (150 kg/m³), metal sheathing. The interior walls solely consist of the 240 mm lightweight concrete (1200 kg/m³), painted at both sides. The roof, for 70 % of the surface area, comprises 2 mm metal sheathing, 300 mm low-density mineral wool insulation (32 kg/m³), asphalt roofing felt; for the remainder, 300 mm heavy-weight concrete (2300 kg/m³) – abstractly representing the concrete TT-beams supporting the roof – replaces the metal sheathing. The slab-on-ground floor is composed of (vapourtight) epoxy paint, 100 mm heavy-weight concrete (2300 kg/m³), 150 mm leca pellets (325 kg/m³), and a sandy soil underneath. More information on the specific modelling of that floor and ground is given in Section 2.3. For the daily hygric response, only the interior fractions of exterior and interior walls are taken up in the model, as they provide the main moisture buffer for daily humidity variations, as described in Section 2.4.

2.2 Yearly hygrothermal behaviour

The yearly simulations of the thermal and hygric climate in the storage space are carried out with the hygrothermal building simulation model BSim, developed by the Danish Building Research Institute [24]. The model allows calculating the hygrothermal behaviour of the interior air and of the building envelope: a one-node model for the interior climate zone is coupled to

a one-dimensional control-volume-based model for each component. The heat and moisture transfer in the walls and roof is virtually one-dimensional, and is therefore easily modelled in BSim. The three-dimensional heat transfer in the floor and ground, on the other hand, clashes with BSim's one-dimensional modelling approach. To resolve that, a specific ground heat transfer approach is suggested in the next section. Moisture transfer in the floor is neglected because of the epoxy paint applied at its top surface. It should finally be noted that heat and moisture buffering in the stored objects cannot be easily integrated in BSim, and has accordingly not been accounted for in the yearly hygrothermal behaviour.

No specific ventilation with outdoor air is implemented in the real building, and hence equally not in the numerical model. Infiltration of outdoor air, via air leaks in the building envelope, is however unavoidable. A blower-door test performed on the building indicates an air change rate of 0.65/h at 50 Pa pressure difference. Based on Sherman [25], this translates to a likely air change rate of 0.04/h under standard conditions. Since Sherman developed this relation mainly for single-family dwellings, this value may be inaccurate for the large building considered here. It is however in agreement with the original design value, and validation of the model below will moreover corroborate its acceptability.

The main interior heat gains stem from people working in the storage space, and the lighting that is required at such times. 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 result in interior heat gains at 5 W/m^2 [26]. Accounting for the limited human presence and the light sectioning translates this to 19 kWh each weekday, implemented as an interior gain of 2.4 kW for 8 hours for every working day. For the exterior climate, the Design Reference Year (DRY) data for Denmark are used. The Danish climate has a yearly average temperature of 7.8°C and relative humidity of 83 %RH.

2.3 Ground heat transfer

A very critical feature in the BSim model is the thermal interaction between the interior zone and the slab-on-ground floor with the underlying ground volume, as those provide an essential part of the interior thermal inertia. This interaction is fundamentally a three-dimensional (3D) process [27], defying BSim's one-dimensional (1D) approach. BSim thus necessitates translating the original 3D process into an equivalent 1D process. That 1D model is to comprise the concrete and leca layers, complemented with a soil layer of uniform thickness: the interior boundary conditions are implemented on the surface of the concrete and the exterior boundary conditions are imposed on the opposite surface of the soil layer. This methodology is outlined below, and will allow the equivalent thickness of the soil layer to be estimated such that the 3D and 1D thermal interactions are equivalent. As a first step, the original 3D process is transformed into a comparable 2D model, which is in turn translated into an equivalent 1D description. While the methodology is developed here for a particular application, it has generic validity and can thus be widely applied. All needed simulations have been performed with HEAT2 (a simulation model for multidimensional heat conduction [28]).

2.3.1 Two-dimensional transfer

Essentially we need to assess the response of a half-infinite soil volume to an excitation with variable interior temperature over a rectangular section of the surface and with variable exterior temperature over the remaining part of the surface. Anderson [29] corroborated that this 3D heat exchange between building and ground can be dependably calculated with an equivalent 2D geometry. Instead of the normal 3D geometry with the building's width and length as defining parameters, a 2D geometry with a length equal to the building's perimeter P and a width equal to half of the building's 'equivalent width' B' can equivalently be utilised:

$$B' = \frac{A}{P/2} \quad (1)$$

with: B' : equivalent width of building [m]
 A : surface area of building [m^2]

P: perimeter of building [m]

Quantifying the thermal interaction between building and ground thus requires the calculation of the 2D heat transfer from a building section with a width $B'/2$, to be multiplied with the perimeter P of the building to obtain the total heat exchange. Such 2D simulations form the start of the methodology and are executed along the ground heat transfer simulation guidelines as put forward in EN ISO 13370 [30]. These guidelines mainly refer to the required dimensions of the calculation domain and to the necessary level of detail for the modelling of the floor. In these simulations, the actual thermal excitation, consisting of a variable interior and exterior temperature, is not imposed directly. Instead it is split into three primary regimes:

- *steady-state*:
  - interior temperature: constant at 1 °C;
  - exterior temperature: constant at 0 °C;
- *transient interior*:
  - interior temperature: a harmonic variation with period 1 year, average 0 °C, amplitude 1 °C, phase angle taken from measured interior temperatures;
  - exterior temperature: constant at 0 °C;
- *transient exterior*:
  - interior temperature: constant at 0 °C;
  - exterior temperature: a harmonic variation with period 1 year, average 0 °C, amplitude 1 °C, phase angle taken from Danish DRY;

Any actual excitation can be recomposed from these three primary regimes, via the principal superposition of linear solutions. The ensuing equivalent 1D ground heat transfer description can thus also be considered correct for other thermal excitations, and is consequently generally valid.

2.3.2 One-dimensional transfer

The soil layer thickness for the equivalent 1D floor construction is first estimated from imposing the equality of the 2D and 1D *steady-state* heat flows, and then verified for agreement on the 2D and 1D *transient interior* and *transient exterior* heat flows (evaluated at the floor's top surface). For our storage space with dimensions 68.0 x 48.3 m², that first estimate gives 11.8 m: the global thermal resistance of the underlying soil domain is hence equivalent to that of a 11.8 m soil layer. Such steady-state estimate guarantees the agreement of the average heat flows, but it does not necessarily ensure the equivalency of the transient thermal interactions between storage and soil. That lack of equivalency is illustrated in Figure 2, which compares the results of the three fundamental simulations (*steady-state*, *transient exterior*, *transient interior*) for the original 2D and equivalent 1D model. The *steady-state* heat flows are naturally in agreement. Small differences are seen for the *transient interior* responses, with 4 % deviations at the heat flow peaks, but these are presumed negligible. Complete disagreement is observed however for the original 2D and equivalent 1D *transient exterior* responses, both in the heat flow amplitude and phase.

A simple translation of the original 2D process to a single 1D equivalent does hence not yield satisfactory results. In reality and in the 2D model, the phase shift between the exterior temperature variation and the corresponding heat flow variation is fairly small near the perimeter of the building, while these heat flows are relatively large and therefore govern the total heat flow; the 11.8 m soil layer in the 1D model can evidently not capture this short-term effect. It may be noted that Figure 2 shows that the exterior temperature variations yields the smallest response, rendering it possibly insignificant. It has to be kept in mind though that responses to a 1 °C excitation are shown, requiring multiplication with the actual temperature difference or amplitude still. As the exterior temperature amplitude often exceeds the interior variation amplitude and the average interior-exterior difference, a sufficiently accurate 1D response to *transient exterior* remains necessary.

To resolve that issue, the original 'half of the characteristic width B'' – 14.1 m for the building considered here – is discretised into 5 separate zones, with respective widths 1 m, 1 m, 1 m,

2 m and 9.1 m (starting from the building perimeter). In the 2D simulations, the heat flows in these zones of the floor are monitored separately and then applied to define 5 equivalent 1D models, each with a specific equivalent soil thickness. This discretisation approach leads to soil thicknesses ranging from 0.9 m (zone closest to the perimeter) to 19.7 m (zone furthest from perimeter). It can be observed in Figure 2 that the original 2D results and the composed 1D results now compare much better concerning their *transient exterior* responses. The discretisation approach clearly allows the 1D model to mimic the smaller phase shifts for the floor zones close to the perimeter as well as the large phase shifts for the floor zones further away from the perimeter. In the BSim model thus, the floor is modelled with 5 proportionally sized floor zones, each with their specific equivalent soil layer thickness.

2.4 Daily hygric behaviour

The daily simulations of the hygric climate inside the storage are performed based on the dynamic vapour balance for the interior air, including the moisture buffering in the building walls and the stored objects [31–34]. The interior air is firstly analysed separately, moisture buffering in walls and objects is added in subsequent stages.

2.4.1 Interior air

The moisture balance for the interior air allows quantifying the vapour pressures and relative humidities in the museum storage space:

$$\frac{\partial M_{v,i}}{\partial t} = G_{v,in} - G_{v,out} \quad (2)$$

with: $M_{v,i}$: vapour mass in interior environment [kg]
 $G_{v,in}$: entering vapour flows [kg/s]
 $G_{v,out}$: exiting vapour flows [kg/s]

Application of the ideal gas law for $M_{v,i}$, and insertion of concrete terms for the moisture flows entering and exiting the interior environment transforms equation 2 into an expression for the time evolution of the interior vapour pressure, which is solved explicitly:

$$\frac{V}{R_v T_i} \frac{\partial p_{vi}}{\partial t} = G_{v,people} - G_{v,dehum} + \frac{nV}{3600 R_v T_i} (p_{v,e} - p_{v,i}) \quad (3)$$

$$p_{v,i}^{t+\Delta t} = (G_{v,people}^t - G_{v,dehum}^t) \frac{\Delta t}{V} R_v T_i^t + \frac{n(p_{v,e}^t - p_{v,i}^t)\Delta t}{3600} + p_{v,i}^t \quad (4)$$

with: V : volume of interior environment [m³]
 R_v : gas constant for water vapour [J/kgK]
 T_i : temperature in interior environment [K]
 $p_{v,i}$: vapour pressure in interior environment [Pa]
 $p_{v,e}$: vapour pressure in exterior environment [Pa]
 $G_{v,people}$: vapour production by human presence [kg/s]
 $G_{v,dehum}$: vapour drainage by dehumidification [kg/s]
 n : air change rate [/h]
 t : time [s]
 Δt : time step [s]

The vapour production by human presence is taken at 60 g/h for 8 person-hours per working day, analogous to the interior heat gains (see section 2.1.3).

2.4.2 Building walls

The original balance is first extended to include hygric interaction with building walls. Fluctuations in the indoor relative humidity result in a storage or release of vapour in the walls, and they hence act as moisture buffer. The moisture balance of equation 2 is extended to:

$$\frac{\partial M_{v,i}}{\partial t} = G_{v,in} - G_{v,out} - G_{v,buffer} \quad (5)$$

$$G_{v,buffer} = A_b \frac{p_{v,i} - p_{v,b}}{1/\beta + d_b/2\delta_b} = A_b \xi_b d_b \frac{\partial}{\partial t} \left(\frac{p_{v,b}}{p_{v,sat}(T_b)} \right) \quad (6)$$

with:

$G_{v,buffer}$:	vapour drainage by moisture buffering [kg/s]
A_b :	surface area of buffering components [m ²]
$p_{v,b}$:	vapour pressure in the buffering layer [Pa]
β :	surface vapour transfer coefficient [s/m]
d_b :	thickness of the buffering layer [m]
δ_b :	moisture permeability of buffer material [s]
ξ_b :	moisture capacity of buffer material [kg/m ³]
$p_{v,sat}$:	saturation vapour pressure [Pa]
T_b :	temperature in the buffering layer [K]

The buffer flow between the indoor air and building walls is thus modelled through the 'effective moisture penetration depth' method [31], which presumes that buffering only takes place in the surface fraction of the wall material. The thickness of this buffer layer d_b is usually assumed equal to the moisture penetration depth:

$$d_b = \sqrt{\frac{t_p \delta p_{v,sat}(T_b)}{\pi \xi}} \quad [m] \quad (7)$$

with: t_p : time period of fluctuation [s]

For the concentrated dehumidification examined here, the period is assumed 24 hours. The moisture capacity and permeability of the walls' lightweight concrete are 38.9 kg/m³ and 3.9 · 10⁻¹¹ s (at 50 %RH), giving a moisture penetration depth of 0.007 m (at 15 °C): just a minimal fraction of the 240 mm walls is thus acting as a moisture buffer for daily fluctuations.

2.4.3 Stored objects

Variations in the indoor relative humidity similarly also yield storage and release of vapour by the objects stored in the storage space: the content of the storage thus equally contributes to the dampening of the interior relative humidity variation. It is very complex though to reliably quantify this interaction as it depends on the amount and the nature of the objects in storage. An approximate quantification allows assessing its basic potential however. Given the many unknowns in relation to the stored objects, moisture buffering in the stored objects is not described with the 'effective moisture penetration depth' approach, as applied earlier. Instead, the 'effective moisture capacity' method [31] is used: this approach presumes that the moisture mass in the stored objects is always in equilibrium with the relative humidity of the interior air. This allows integrating their moisture buffering effect by multiplying the moisture capacity of the interior air with an enhancement term M:

$$M \frac{\partial M_{v,i}}{\partial t} = G_{v,in} - G_{v,out} - G_{v,buffer} \quad (8)$$

with: M : multiplication factor for air moisture capacity [-]

The value of M is difficult to determine, but in this investigation a conservative value of 5 has been chosen in order to quantify the moisture buffer capacity of the stored objects. A higher value will give even more stable relative humidities in the storage. It is mentioned again that this hygrothermal interaction with the stored objects is only considered in the 'daily hygrothermal behaviour' and not in the 'yearly hygrothermal behaviour'.

3. POTENTIAL OF PASSIVE CONDITIONING

In this section on full passive conditioning, the yearly hygrothermal behaviour model (section 2.2 & 2.3) is used to quantify the interior temperature and relative humidity for the fully passively conditioned storage space, without any auxiliary conditioning hence. A steady-periodic solution is attained after 10 years of simulation, and that simulation result is retained for ana-

lysis here: the resulting hourly values and monthly averages of interior temperature and relative humidity are shown in Figure **Error! Reference source not found.**.

3.1 Validation of numerical model

To firstly confirm the reliability of the 'yearly hygrothermal climate' model, temperatures simulated with the BSim model are confronted with temperatures measured during 2007 in the actual Vejle storage (values utilised are the averages from measurements in halls A, C, and D). Measured data are also available for the relative humidity, but a comparison with these is not rewarding: the actual storage space applies dehumidification, while the simulations do not include such conditioning. Figure 4 shows the confrontation between the simulated and measured interior temperatures: it is obvious that the agreement between both is far from satisfactory. It should be noted though (see Figure 4 bottom) that the exterior temperatures for 2007 do not match with the DRY data: the average and amplitude of the simulated exterior temperatures are substantially lower than those of the measured exterior temperatures.

A correction is therefore due. In both measurement and simulation, the interior temperatures result from the balance of the interior heat gain and the heat loss to the exterior. As the heat gain can be assumed to be evenly distributed over the whole year, the interior temperatures' average and amplitude form a direct response to the exterior temperatures' average and amplitude: higher values of the latter give higher values of the former. This simple principle can be used to correct the simulated interior temperatures toward a virtual forcing by the measured exterior temperatures (instead of the DRY values): the average of the interior temperatures is augmented with the difference between the averages of the 2007 and the DRY exterior temperatures, while the amplitude of the interior temperatures is multiplied by the ratio of the amplitudes of the 2007 and the DRY exterior temperatures.

The obtained corrected interior temperatures are also shown in Figure 4. While the correction is based on exterior air temperatures only – excluding all other climate factors –, it is concluded that a fair agreement between simulations and measurements is obtained. That correspondence is not flawless for the first few months of 2007 though, but this difference is attributed to the fact that 2006 was even warmer than 2007. The response during the first few months of 2007 is affected by these 2006 conditions, and hence the underestimations in the corrected simulations still; this particular effect can however not be easily inserted in the correction. All in all though, the reliability of the developed model is assumed confirmed.

3.2 Full passive conditioning ?

To correctly gauge the dependability of full passive conditioning for museum storage spaces, the graphical data from Figure 3 are translated to numeric outcomes. The monthly averaged temperatures and relative humidities are converted into a yearly average and variation (difference between maximum and minimum monthly value); the hourly temperatures and relative humidities are transformed into daily variations (difference between maximum and minimum daily value), of which the average, 90-percentile and maximum value are retained (Table **Error! Reference source not found.**). The yearly average temperature is fair, as human comfort is no priority in a museum storage space. The yearly and maximum daily temperature variations are still in line with ASHRAE's top conservation class AA [2]. The building's large thermal inertia hence obviously succeeds in sufficiently dampening the temperature fluctuations. For the relative humidity, on the other hand, its daily variations exceed the accepted 5 %RH for 10 % of the time and its yearly variation is too high as well. Both may yield mechanical damage. The hygric inertia in the building thus does clearly not suffice to adequately dampen the relative humidity variations in the storage space. The yearly average is moreover far too high as well, potentially leading to biological damage. And while including moisture buffering in stored objects may well diminish the excessive relative humidity variations, it would not remedy the overly high average relative humidity. It is hence obvious that full passive conditioning of the museum storage space results in unacceptable interior relative humidities.

This is no surprise in the end, as the exterior climate of Denmark is bound to render full passive conditioning of museum storage spaces impossible. Without any interior heat or moisture gains, the yearly average temperature and vapour pressure will equilibrate with their exterior counterparts. Based on the Danish DRY, this boils down to 7.8 °C and 930 Pa, which is equivalent to 88 %RH. Interior heat gains and solar gains at the building surfaces boost the actual average interior temperature to 10.2 °C, lowering the relative humidity to about 75 %. This general level of relative humidity can also be observed in Figure 3. Such conclusion is equally valid for many other maritime and/or cold climates in the world, with similarly high relative humidities [35]. Full passive conditioning must be considered an illusion thus, notwithstanding the positive opinions given in [15-16]. Such findings confirm the conclusion of [17], stating that conservation heating or auxiliary dehumidification are a must to ensure acceptable conservation conditions. It should be kept in mind, though, that a very strict definition of 'fully passive' has been used: maximal isolation of the interior environment from the exterior environment is to produce the desired indoor climatic conditions. In a more free definition of 'passive conditioning', the passive solar gains could be designed such that they lead to higher interior temperatures, in turn lowering the interior relative humidities.

4. REDUCTION OF DEHUMIDIFICATION LOAD

The section above has demonstrated that full passive conditioning does not emerge as a dependable conditioning solution for museum storage spaces. Conservation heating or auxiliary dehumidification are required to maintain acceptably low relative humidity levels. This finding is also corroborated by the Vejle storage, where permanent dehumidification is applied. This choice for dehumidification over heating is based on the conclusions of Rhyll-Svendsen et al [36], comparing the energy consumption for conservation heating and auxiliary dehumidification for a museum storage space very similar to the one investigated here. They state that, for an air change rate below 6 times per day, dehumidification is the best solution. This section therefore explores the options to reduce the dehumidification load, to lower the energy consumed for the conditioning of museum storage spaces.

4.1 Influence of thermal climate

A relative humidity of 50 % is imposed as the dehumidification set point. A mass balance of human vapour production and vapour transfer by air infiltration and exfiltration allows the expected dehumidification load to be calculated. As the interior relative humidity remains constant at 50 %, all moisture buffering in walls and objects is absent. For the storage space in its current state, the dehumidification load comes to 14710 liter per year: it peaks in summer, due to the higher interior temperatures and humidities, while it is relatively lower in winter. In what follows, various design changes are examined with respect to their effect on the required dehumidification, focusing on thermal insulation and air tightness improvements. The potential of the thermal insulation measures can be illustrated from the effect of changes in the current interior temperature average and variation: a 1 °C rise in the yearly average reduces the dehumidification with 14 %, while a 1 °C drop amplifies it with 13 %; increasing/decreasing the yearly temperature variation with 50 % reduces/amplifies it with respectively 6 % and 4 % (higher summer temperatures lower the peak in dehumidification, dominant in the global load). Five separate thermal insulation measures – one for the walls, one for the floor, three for the roof – are investigated in this section, in addition to the current construction. Complementarily, one air tightness measure is examined, and finally, one compiled optimal solution. A synopsis of the different variants investigated is gathered in Table 2.

4.2 Analysis of simulation results

All simulation results are collected in Figure 5. The core simulation results are the dehumidification load, the interior temperature and the relative reactivity. As before, the dehumidification load is computed from a mass balance of human production and air in-/exfiltration. Interior temperatures are described by the yearly average, yearly variation and the average daily

variation. The latter is a measure for potential mechanical deterioration, since the daily temperature fluctuations control the short-term thermal expansion and shrinking. Relative humidity variations have a similar impact, via the hygric strains and stresses, but these are avoided by the dehumidification. The effect on the potential chemical deterioration is quantified by a relative reactivity, for which the 'isoperm' concept is used [37], calculating the relative reaction rate for an abstract hydrolysis at two different temperatures:

$$RR_i = \left(\frac{T_{2,i} + 860}{T_{1,i} + 860} \right) 10^{\left(169.4 \Delta H \left(\frac{1}{T_{2,i} + 860} - \frac{1}{T_{1,i} + 860} \right) \right)} \quad (9)$$

with: RR : relative reaction rate [-]
 $T_{2/1,i}$: actual and reference temperature at hour i [°C]
 ΔH : activation energy for hydrolysis reaction [KJ/mole]

The activation energy is taken at 100 KJ/mole [37], the reference temperature is assumed at 10 °C for the whole year. Equation 9 thus converts all hourly temperatures into a relative reaction rate, relative to the rates obtained in a museum storage space which would be kept at 10 °C throughout the year. The yearly average value for all 8760 RR is assumed a measure for the potential chemical deterioration.

4.3 Impact of insulation measures

Figure 5 results in various distinct observations. Firstly, increasing the thermal resistance of the storage's walls (variant 2) has virtually no influence: the yearly average temperature and temperature variation go up slightly, the daily variations go down slightly. The dehumidification load subsequently decreases with 4.8 % relative to the original building, while the chemical decay potential increases with 3.7 %. Increasing the thermal resistance of the floor (variant 3) mainly has an influence on the yearly variation. The dimensions of the building render the ground volume under the building already fairly insulating: adding the insulation does not change its U-value significantly, and thus the limited effect on the yearly average. That insulation neither affects the short-term inertia of the floor, and hence the restricted impact on the daily variations. The floor insulation lessens the thermal interactions with the ground volume though, and therefore the long-term thermal inertia of the building, reflected by a higher yearly variation. This larger yearly variation results in a lower dehumidification load, and a higher chemical decay, but again the impacts are far from dramatic.

Increasing the thermal resistance of the roof (variant 4) leads to a decreased yearly average, opposite to the two earlier variants. This is attributed to solar radiation absorbed by the roof surface, which obviously results in a sol-air temperature above the interior temperature. This implies that the roof actually delivers heat to the interior zone. This is confirmed by lowering the thermal resistance of the roof (variants 5 and 6), in turn increasing the yearly averages of the interior temperature. While this decreases the dehumidification somewhat, the daily temperature variations grow significantly, translating to a higher risk on mechanical deterioration. All in all though, the impact of the thermal insulation measures is quite limited: the dehumidification loads can be brought down with some 5 to 10 %, at most. But those reductions often come at the expense of higher mechanical decay potentials, through larger daily temperature variations.

4.4 Impact of air tightness measures

The sole efficient measure is reducing the infiltration rate (variant 7). While the influences on the overall thermal response and the potential mechanical and chemical deterioration remain limited, the dehumidification load is greatly reduced. The original storage space with an infiltration rate of 0.04 ACH requires 14710 l/yr in dehumidification, whereas the 0.01 ACH configuration needs only 3560 l/yr. The infiltration of exterior air is indeed the key moisture source for the interior climate, and any reduction of the infiltration rate evidently leads to a reduction of the required dehumidification. The combination of 0.01 ACH, 50 cm wall insulation, 15 cm floor insulation, 20 cm roof insulation (variant 8) finally reduces this further to 3140 l/yr. Such

solution does slightly amplify the daily temperature variation (up 17 % relative to the original) and the relative reactivity (up 27 % in comparison to the original). But all in all, these can be assumed minor and are considered the price to pay for the 79 % reduction of the original dehumidification load.

5. CONCENTRATED DEHUMIDIFICATION

The section above has shown that full passive conditioning of museum storage spaces is often thwarted by the commonly high levels of exterior humidity, which yield unfavourably high humidity conditions in the building. This conclusion is corroborated by the experience in the existing building, where continuous dehumidification is required to keep the relative humidity at 50%. An economic and ecologic enhancement of that dehumidification is possible though, by using concentrated dehumidification during a part of the day instead. The building hygric inertia – of interior air, building walls, stored objects – then is to ensure that the interior relative humidity does not vary substantially, and can be left free-running for the other part of the day. Such concentrated dehumidification can more easily be powered by renewable energy, which is often of time-limited nature. One could, for example, use solar-generated photovoltaic electricity during the day, or excess wind-generated electricity during the night, or .... No matter what the choice, the use of renewable energy sources is to reduce the economic and ecologic impact of the conditioning of the museum storage space.

5.1 Timing of concentrated dehumidification

Below, the resulting relative humidity variations are simulated with the daily hygric behaviour models put forward in Section 2.4, in combination with the temperatures predicted previously with the yearly hygrothermal model in Section 3. In all cases, the variation of interior relative humidity over a summer day is assessed, as that gives the worst-case scenario. The current building – current construction, 0.04 ACH – is analysed in detail first, the new building – optimised construction, 0.01 ACH – is tackled in a following paragraph.

In this illustrative investigation, the museum storage space is left free-running from 18.00h to 12.00h, while dehumidification is employed from 12.00h to 18.00h. The latter interval usually entails the highest moisture load for the storage space, because of the high vapour pressure in the exterior environment at those times. A concentrated dehumidification during this high-load interval will hence reduce the relative humidity variation during the free-running interval. The relative humidity in the building slowly rises from its initial value of 50 % during the free-running phase, and is brought back to that initial value during the dehumidification phase. In each case hence, the needed dehumidification is calibrated such that the relative humidity is brought back down to the 50 % level at the end of the 24-hour cycle.

5.2 Standard air tightness building

In a first simulation, only the hygric inertia of the interior air is considered. The resulting variation of the interior relative humidity is shown in Figure 6. The relative humidity rises from its original 50 % up to 75.5 % at the end of the 18 hour free-running phase, a utterly unacceptable fluctuation. However, the hygric interaction with the building walls and the stored objects has not been considered yet.

The building's interior and exterior walls are 240 mm light weight concrete, but painted with a cement-based white paint with high vapour permeability. Figure 6 also shows the relative humidity variations when including the moisture buffering in the building walls, both without and with paint. Without paint, Figure 6 indicates that the rise in interior relative humidity is now limited to 58.2 %; with paint however, the buffering effect is all but eliminated. The paint's vapour diffusion resistance has been modelled by reduction of the surface transfer coefficient β from $2.0 \cdot 10^{-8}$ s/m to $2.0 \cdot 10^{-10}$ s/m. The surface transfer coefficient is thus equivalent to 1 cm of air, while the paint is equivalent to 100 cm of air. While such low resistance can indeed be characterised as 'very vapour open', it nonetheless reduces the moisture accessibility of the

walls with a factor 100. And Figure 6 makes it clear that such almost completely nullifies the moisture buffering by the walls.

Variations in the interior relative humidity similarly also result in storage or release of vapour by the objects stored in the storage space: the content of the storage thus equally contributes to the stability of the indoor climate when concentrated dehumidification is used. It is very difficult though to quantify this interaction, as it depends on the amount and the nature of the stored objects. An approximate quantification will however allow gauging its basic potential. The influence of including moisture buffering by the stored objects is shown in figure 7: it demonstrates that the relative humidity now peaks at 56.6 %, when only the stored objects are accounted for. The stored items therefore play a significant role in stabilizing the relative humidity, by absorbing and releasing moisture. When the buffering in unpainted building walls is added to the simulations, the interior relative humidity only rises to 54.3%. This brings us just within the boundaries of ASHRAE's top conservation class AA [2].

5.3 Improved air tightness building

The section above has demonstrated that concentrated dehumidification can be considered, since the resulting variations in interior relative humidity remain restricted to a few percent, if sufficient moisture buffering in the building walls and in the stored objects is possible. In the analysis above, infiltration of moist exterior air is the major moisture source, and thus crucial to the response of the interior environment to concentrated dehumidification. Better air tightness may thus further advance the potential of concentrated dehumidification.

The results for a more airtight building, with a reduced air change rate of 0.01/h, are brought together in Figures 8 and 9. When only the hygric inertia of the interior air is considered, the higher air tightness lowers the peak relative humidity to 58 % instead of the 75 % previously. Inclusion of moisture buffering in building walls reduces this peak value to 52 % and addition of moisture buffering in stored objects brings that peak value further down to 51 %: these values imply that concentrated dehumidification yields a mere 1 to 2 %RH variation over a day, depending on the moisture buffer capacity of the collection of stored objects. It can hence be concluded that, for a adequately airtight building, the hygric inertia of the interior air, building walls and/or stored objects is sufficient to allow concentrated dehumidification, without major variations in interior relative humidity.

6. CONCLUSION

For optimal longevity of the stored objects, museum storage spaces require a very stable interior climate, with solely minimal and slow fluctuations in temperature and relative humidity. Often extensive air conditioning is installed to provide such indoor conditions, with resultantly high economic and ecologic costs. These are currently motivating a paradigm change toward passive control: a storage with a high thermal and hygric inertia, enclosed by an envelope with high thermal and hygric resistance, should sufficiently stabilise the interior climate, with resultantly (virtually) no need for mechanical air conditioning. The dependability of passively conditioned museum storage spaces had only been corroborated though for applications where some indirect heating was available, or where particular ventilation strategies were applied.

This paper hence first analysed the reliability of full passive conditioning for museum storage spaces, and indicated that this approach often leads to excessive interior humidities, and accordingly that passive conditioning is an illusion for most climates. Auxiliary dehumidification is hence necessary to provide good conservation conditions, and the article secondly examined how the dehumidification load could effectively be reduced. The study revealed that the impact of thermal insulation improvements is minor, while an intervention in the air tightness has considerable effect. The combination of the two brings the dehumidification needs down with 79 %, with a small price to be paid in the form of slightly increased potentials for mechanical and chemical decay.

Having shown that the dehumidification can be reduced but not eliminated, the paper looked into the potential of concentrated dehumidification, which can more easily be powered by renewable energy. For an air tight museum storage space, it was shown that the hygric inertia of the interior air, the building walls and the stored objects is sufficient to allow dehumidification during a part of the day only while leaving the storage space free-running during the rest of the day, with only minimal fluctuation in the interior relative humidities. Such concentrated dehumidification permits the use of solar-generated photovoltaic electricity during the day, or of excess wind-generated electricity during the night. That option will in turn significantly decrease the economic and ecologic costs for the air conditioning of museum storage spaces.

ACKNOWLEDGEMENTS

We thank Lise Ræder Knudsen and Louis Lange Wollesen, from Vejle County Cultural Heritage Centre, Denmark; and master students Barbara Tognolo and Javier Menendez Gabelles, from Technical University of Denmark.

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TABLES

1. Processed results for interior temperature and relative humidity
2. Overview of different investigated designs for the storage space

Table 1

	<i>temperature [°C]</i>	<i>relative humidity [%]</i>
yearly average	10.2	69.4
yearly variation	10.1	22.6
average daily variation	0.20	2.77
maximum daily variation	0.53	14.78
90-percentile daily variation	0.33	5.07

Table 2

<i>case</i>	<i>construction</i>
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

FIGURE CAPTIONS

1. Plan of the Vejle museum storage space with the four halls (top) [19], exterior view on the building (centre), and interior view showing the mezzanine construction (bottom)
2. Confrontation of thermal responses from the original 2D model and the equivalent 1D model (top) and from the original 2D model and the 5-zone-composite equivalent 1D model (bottom)
3. Hourly values (top) and monthly averages (bottom) for the simulated interior temperatures and relative humidities
4. Simulated and measured interior temperatures, together with the corrected interior temperatures and the simulated interior relative humidity (top), simulated and measured exterior temperatures (bottom)
5. Yearly average, yearly variation and daily variation of interior temperature (top), yearly average chemical decay potential and yearly dehumidification load (bottom), for the eight solutions examined
6. Summer day interior relative humidity variation under concentrated dehumidification, for the cases of hygric inertia by interior air and by interior air and building walls
7. Summer day interior relative humidity variation under concentrated dehumidification, for the cases of hygric inertia by interior air and stored objects and by interior air, stored objects and building walls
8. Summer day interior relative humidity variation under concentrated dehumidification, for the cases of hygric inertia by interior air and by interior air and building walls, for the more air tight building
9. Summer day interior relative humidity variation under concentrated dehumidification, for the cases of hygric inertia by interior air and stored objects and by interior air, stored objects and building walls, for the more air tight building

FIG 1. Plan of the Vejle museum storage space with the four halls (top) [19], exterior view on the building (centre), and interior picture showing the mezzanine construction (bottom)

FIG 2. Confrontation of thermal responses from the original 2D model and the equivalent 1D model (top) and from the original 2D model and the 5-zone-composite equivalent 1D model (bottom)

FIG 3. Hourly values (top) and monthly averages (bottom) for the simulated interior temperatures and relative humidities

FIG 4. Simulated and measured interior temperatures, together with the corrected interior temperatures (top), simulated and measured exterior temperatures (bottom)

FIG 5. Yearly average, yearly variation and daily variation of interior temperature (top), yearly average chemical decay potential and yearly dehumidification load (bottom), for the eight solutions examined

FIG 6. Summer day interior relative humidity variation under concentrated dehumidification, for the cases of hygric inertia by interior air and by interior air and building walls

FIG 7. Summer day interior relative humidity variation under concentrated dehumidification, for the cases of hygric inertia by interior air and stored objects and by interior air, stored objects and building walls

FIG 8. Summer day interior relative humidity variation under concentrated dehumidification, for the cases of hygric inertia by interior air and by interior air and building walls, for the more air tight building

FIG 9. Summer day interior relative humidity variation under concentrated dehumidification, for the cases of hygric inertia by interior air and stored objects and by interior air, stored objects and building walls, for the more air tight building