PASSIVE HYGROTHERMAL CONTROL OF A MUSEUM STORAGE BUILDING

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ABSTRACT

For optimal conservation 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 HVAC is installed to provide such stable indoor conditions, which results in a great amout of $C0_2$ emission. The purpose for this paper is to show that it is possible to reach the goal of using renewable energy for museum storage buildings by rethinking the strategy for the dehumidification design and in this way contribute to a $C0_2$ neutral environment. The solution is to construct a very airtight building and use concentrated dehumidification.

INTRODUCTION

According to the 2010 recast of the European Energy Performance of Buildings Directive – EPBD (Directive 2010/31/EU), new buildings must be nearly zero energy buildings, while comprehensive energy renovations are to be implemented in existing buildings. To reach such targets, it is required that buildings are operated with optimal degree of energy efficiency, by introducing measures as thermal insulation, energy efficient windows, and heat recovery. Moreover, it is essential to integrate passive and active energy measures, possibilities of energy storage, and renewable energy resources. The final target is finding a cost-effective way of coupling energy conservation policies with the development of energy smart grids, assuring the implementation of $C0_2$ neutral communities.

In this paper, we will apply these concepts to the design of museum storage buildings, demonstrating that their energetic optimisation necessitates radically different concepts. Instead of transmission and ventilation losses, the main concern here is the dehumidification load, due to the specific climate conditions required for conservation of historic objects.

Conservation of historic objects

Generally, the conservation of historic objects benefits from stable temperatures and relative humidities. Strong variations in relative humidity and temperature may result in mechanical decay, caused by the related dimensional changes (Padfield 1998). High humidity levels may yield biological decay, as they increase the activity of fungi and moulds. High temperature levels finally may give chemical decay, as they augment chemical reactivity (Padfield 2005).

Generally, extensive air conditioning is implemented to ensure such stable interior environment in museum storages and museum displays. That option however commonly results in significant energy consumption, which is detrimental both economically and ecologically (Padfield 2007, Padfield et al. 2007, Padfield 2008). An alternative approach is hence promoted in scientific literature (Christoffersen 1995, Padfield et al. 2007, Padfield 2008): full passive conditioning, in which the thermal and hygric inertia of the construction primarily provide the stable interior climate, and no actual air conditioning is required.

It will introductorily be shown that such fully passive conditioning does not perform acceptably in most climates, and that active dehumidification remains required. The core section of this paper focuses on reducing that dehumidification load, which forms a key share of the overall energy consumption. In that optimisation, standard measures like increased thermal insulation and improved heat recovery are shown not to be important. Instead, air tightness and concentrated dehumidification are put forward.

Museum storage in Denmark

The development in this paper is exemplified with an actual museum storage building in Vejle, used as calculation object throughout. The conclusions from the study are of course more generic, and applicable to a wide range of museum storage buildings.

In 2003, sixteen regional museums in Western Denmark decided to construct a shared storage facility in Vejle (figures 1 and 2).

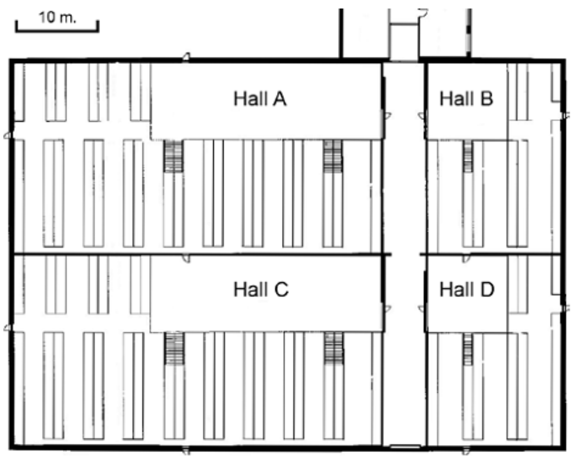

Figure 1 Plan of the museum storage with four halls (Knudsen and Rasmussen 2005).

Figure 2 Exterior view on the main storage building after completion (Photo Christensen).

Figure 3 Picture of the interior of the museum storage showing the mezzanine construction (Photo Conservation Centre).

The current building design already incorporates passive control concepts: thermal inertia is provided by the thick walls, ground floor and underlying soil volume, whereas hygric inertia is provided by the thick walls of light-weight concrete. The design promises stated that a few years of dehumidification would reduce the moisture contained in the fresh construction to a level corresponding with the desired interior climate. After this initial stage, passive controls would eliminate all further need for dehumidification.

The museum storage consists of four halls separated by a corridor (two smaller halls B, D, two larger halls A, C), figure 1. In the museum storage 75 % of the area of the four halls contains a mezzanine construction, figure 3, with a floor of metal grates. The four halls are divided into areas with specific climates, according to requirements for the different collections (Knudsen and Rasmussen, 2005):

- A, C, D: 4122 m^2, 45-60 % RH, 6-17 ºC.
- B: 658 m^2, 40 % RH, 10-17 ºC.

The floor is covered with impermeable epoxy paint, to protect the floor against mechanical wear, and to keep it clean. This epoxy paint of course reduces the hygric inertia of the floor. The walls are painted with white paint of high vapour permeability.

HEAT & AIR TRANSFER MEASURES

The energetic optimisation of the storage building solely based on heat and air transfer measures has been presented in an earlier publication (Christensen et al. 2010), the results of which will be summarised here. Introductorily, the originally promised 'fully passive conditioning' will be critically evaluated.

Method of investigation

The hygrothermal behaviour of the building was modelled with BSim, developed by the Danish Building Research Institute (BSim 2005). While most of the constructions could easily be implemented, the thermal behaviour of the large ground volume below the floor required a specific approach. Bsim, like many other building energy models, handles mainly one-dimensional heat transport through components, while ground heat transfer is essentially a three-dimensional process. To that aim an equivalent one-dimensional description for the floor and ground was deduced from multidimensional heat transfer simulations with Heat2. In (Christensen et al. 2010) it is demonstrated that this equivalent approach forms a decent integration of multidimensional behaviour in one-dimensional building energy models. The same paper also put forwards a satisfactory validation of the model, by confronting simulations to measurements.

Fully passive conditioning

Notwithstanding the design promise, continuous dehumidification is needed to maintain acceptable humidity levels in the storage, even now after five years of use. Thorough investigation of the building design and management in (Christensen et al. 2010) showed that the promise of 'a fully passively conditioned storage building' is an illusion. With the yearly average exterior temperature and vapour pressure in Denmark at 7.8 °C and 930 Pa, a fully passively conditioned building would come to a yearly average temperature and vapour pressure of 10.2 °C and 930 Pa. The interior temperature is somewhat higher than exterior, due to interior heat sources (lights and humans); since no real interior moisture sources are present, the interior vapour pressure is similar to the average exterior value. These interior conditions translate to a yearly average relative humidity of 75 %, far above the desired levels. It is noted that similar conclusions would be reached for many other European climates.

Having eliminated the fully passive conditioning, active air conditioning appears as a requirement for obtaining an acceptable interior climate. Two main options are available in that respect: conservation heating and dehumidification. Conservation heating targets an increased indoor temperature to reduce interior relative humidities, dehumidification on the other hand targets the relative humidities directly. 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 the cheaper solution. Moreover, conservation heating increases the global temperature level, which negatively influences the chemical deterioration of the stored objects, the chemical reaction rate being proportional to the temperature. Dehumidification on the other hand allows for lower interior temperature levels, hence improving the potential conservation.

Dehumidification reduction

In an effort to reduce the necessary dehumidification, a number of thermal measures was investigated first (Christensen et al. 2010). This primarily focused on additional insulation in walls, roof and floor, and on the airtightness of the building. An overview of the different measures is found in Table 1, an overview of their effectiveness is shown in Figure 4.

Table 1
overview of heat and air transfer measures

case	description of measures
1	originally: 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	*combination of 2, 3, 5 and 7*

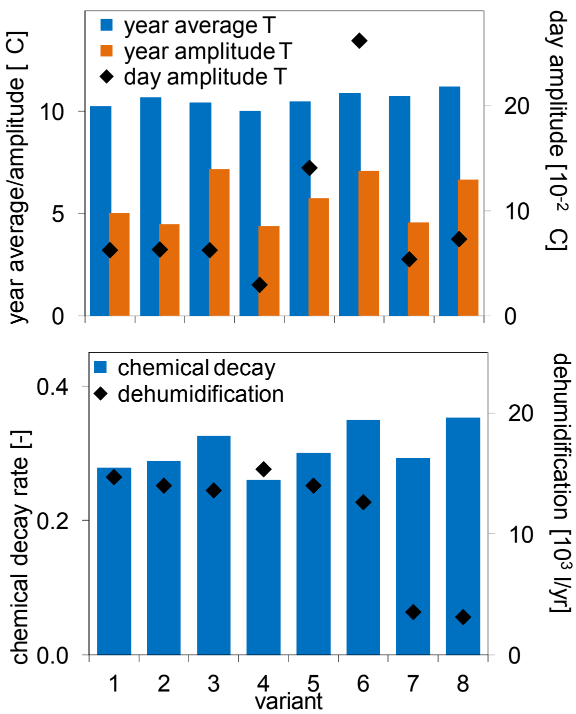

Figure 4 Overview of influences of heat and air flow measures on the dehumidification load (Christensen et al. 2010).

Figure 4 clearly indicates that heat and air flow measures do not significantly change the temperature levels in the building, and thus do not lower the dehumidification load via 'indirect conservation heating'. To reduce the dehumidification load, only one strong solution exists: an airtight building. An increased air tightness reduces infiltration, and hence the amount of vapour that comes into the storage building.

CONCENTRATED DEHUMIDIFICATION

In the previous paragraph, it has been described that the general level of exterior humidity is too high, giving unfavourable humidity conditions in the interior environment. The storage building therefore requires continuous dehumidification to maintain the relative humidity at 50%. This implies that considerable energy is consumed, forming the largest component of the current running cost. The current dehumidification settings allow for an economic and ecologic optimasation however, by use of concentrated dehumidification during a small part of the day. The hygric inertia of the building walls and stored objects then ensures that the building humidity can be left free-running for the rest of the day.

The concentrated dehumidification allows providing the dehumidifiers with renewable energy, usually of time-limited nature. For instance, excess wind energy during the night could be employed, or solar systems during the day. The analysis below gives an onset to concentrated dehumidification, to illustrate its potential. The study imposes six hours of dehumidification and 18 hours of free running, as a possible example. Other regimes will give similar conclusions. Below, the building is analyzed first with a standard natural ventilation of 0.04 ACH, followed by an analysis of a more airtight building with just 0.01 ACH.

Studying the humidity variations resulting from the introduced concentrated dehumidification requires developing a moisture balance for the indoor air of the storage building, including the hygric interactions with the building walls and the stored objects. First, only the indoor air is analysed, the interactions with walls and objects are added later on.

Moisture balance for the air

The moisture balance for the indoor air allows quantifying the vapour pressures and relative humidities:

$$\frac{\partial M_{v,i}}{\partial t} = G_{v,in} - G_{v,out} \tag{1}$$

Application of the ideal gas law for $M_{v,i}$ and insertion of concrete terms for moisture entering and exiting the building transforms equation 1 to an expression for the time evolution of the interior vapour pressure, which is solved explicitly:

$$\frac{V}{R_v T_i}\frac{\partial p_{vi}}{\partial t} = G_{v,people} - G_{v,dehum} + \frac{nV}{3600\, R_v T_i}\left(p_{v,e} - p_{v,i}\right) \tag{2}$$

$$p_{v,i}^{t+\Delta t} = \left(G_{v,people}^{t} - G_{v,dehum}^{t}\right) * \frac{\Delta t}{V} R_v T_i + \frac{n\left(p_{v,e}^{t} - p_{v,i}^{t}\right)\Delta t}{3600} + p_{v,i}^{t} \tag{3}$$

The required dehumidification rate is calculated as follows. The dehumidification required to maintain 50 %RH day round is calculated first, from a moisture mass balance for the interior air similar to 2. To account for only six (instead of 24) hours of dehumidification, the result is multiplied with 4 to obtain the needed concentrated dehumidification rate. This method is somewhat approximate, as it neglects the interaction with the building walls and stored objects. That explains why the final relative humidities in our calculations sometimes exceed their initial value of 50 %RH.

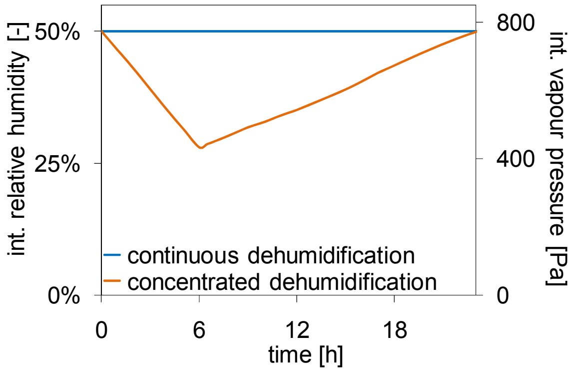

Figure 5 Indoor relative humidity simulated for the second day of July. The comparison shows the evolution of interior relative humidity resulting from continuous and concentrated dehumidification.

The study is performed for a summer and winter day, representing two extreme conditions. Only the results for the summer days are shown here, since they give the worst-case scenario. If the initial relative humidity in the storage building is 50 % at the onset of the concentrated dehumidification, the lowest relative humidity reached in the indoor air is 28 %. The moisture brought in by the infiltration brings this humidity back to 50 % in the other 18 hours of the day, after which the cycle recommences, see figure 5. During a winter day, the lowest relative humidity is 33% RH.

It can be easily concluded that a reduction of the relative humidity from 50% to 28% during a six hour period is completely unacceptable. Until now though, the hygric interaction with the building walls and the stored objects has not been considered yet. To include those, the original indoor air moisture balance is to be extended.

Hygric interaction with building walls

This paragraph first extends the original balances to account for a hygric interaction with building walls. Variations in the indoor relative humidity result in a storage or release of vapour in the walls, which implies that they will act as a moisture buffer.

Interior and exterior walls are 240 mm light weight concrete, painted with a cement-based white paint of high permeability. Originally, the storage building was designed to be completely passively controlled. The thick walls were intended to work as a moisture buffer over a period of up to one year. In that case, the effect of the paint on the buffering capacity is limited. It has been shown though that such full passive control is an illusion and that year-round dehumidification is required. This of course wholly shortcuts the moisture buffering in the walls, as the dehumidification maintains a stable interior relative humidity, which precludes moisture storage and release by the building walls. If the concentrated dehumidification is applied however, daily variations in indoor relative humidity will produce moisture buffering in the building walls on a shorter time scale. For these time scales, a paint layer has a significant influence, as shown below.

To account for the interaction between indoor air and building walls, the moisture balance of equation 1 needs to be extended:

$$\frac{\partial M_{v,i}}{\partial t} = G_{v,in} - G_{v,out} - G_{buffer} \qquad (4)$$

$$G_{buffer} = A\,\frac{p_{v,i} - p_{v,b}}{{}^{1}/_{\beta} + {}^{d_b}/_{2\delta}} = A\xi d_b \frac{\partial}{\partial t}\left(\frac{p_{v,b}}{p_{v,sat}(T_b)}\right) \qquad (5)$$

The buffer flow between the indoor air and building walls is hence modelled through the ‘effective moisture penetration depth’ approach (Janssen et al. 2009) which assumes that buffering only takes place in a surface layer of the walls. The thickness of the buffer layer d_b is assumed equal to the moisture penetration depth d_p, defined as:

$$d_p = \sqrt{\frac{t_p \delta p_{v,sat}(T_b)}{\pi\xi}} \quad [m] \qquad (6)$$

For the concentrated dehumidification studied here, the period is assumed 24 hours. Moisture capacity and permeability of the lightweight concrete at 50 %RH are 38.9 kg/m^3 and 3.9·10^{-11} s. These values result in a moisture penetration depth of 0.005 m. Only a small fraction of the 240 mm walls is hence working as a buffer material on a daily basis.

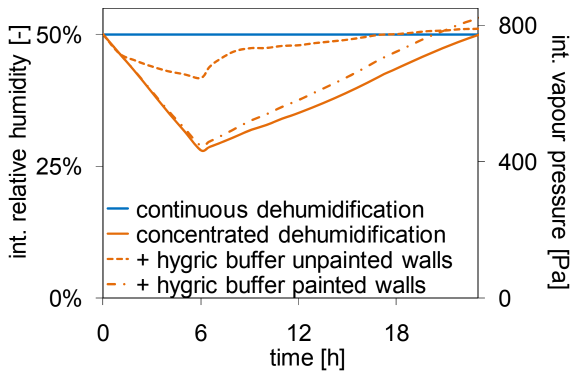

Figure 6 Indoor relative humidity simulated for the second day of July. The comparison shows the evolution of interior relative humidity resulting from continuous and concentrated dehumidification, with inclusion of the hygric buffering by unpainted and painted walls.

The equation system 4 and 5 can be now solved for the vapour pressure of the interior air and of the buffer layer, and the former can be translated to variations of the indoor relative humidity. For the summer day figure 6 now shows that the interior relative humidity declines from 50% to 42%. The comparison with the drop down to 28% in the paragraph before shows that including the moisture buffering in the unpainted building walls has a stabilising influence.

Regrettably though, the walls in the storage building have been painted, albeit with a 'vapour open paint'. It has not been possible to get dependable data on the paint's vapour permeability: Rasmussen (2007) states that its moisture transport resistance is smaller than 1 GPa·m·s/kg.

This resistance has been modelled by reduction of the surface transfer coefficient β from $2.0 \cdot 10^{-8}$ s/m down to $1.0 \cdot 10^{-9}$ s/m. Under normal conditions the surface transfer coefficient is equivalent to 1 cm of air; the paint is hence equivalent with 20 cm of air. Such low resistance can indeed be characterised as a 'very vapour open paint'. Nevertheless, the paint reduces the 'accessibility' of the walls with about a factor of 20. Whereas this may have a minor impact on the yearly buffering (which was aimed for in the original design), the effect of painted versus unpainted walls on the daily buffering is illustrated in figure 6: it is evident that the moisture buffering by the walls is almost completely eliminated.

Hygric interaction with stored objects

Variations in the indoor relative humidity similarly also result in storage or release of vapour by the objects stored in the storage building. The content of the storage equally contributes to the stability of the climate when concentrated dehumidification is used. It is however very difficult to quantify this interaction, as it depends on the amount and the nature of the stored objects. An approximate quantification will allow assessing its basic potential though. Before actually implementing concentrated dehumidification, an experimental study in the current storage building would be of great importance to verify the predictions made here.

Given the various unknowns in relation to the stored objects, moisture buffering in the stored objects does not allow quantification with an 'effective moisture penetration depth' approach, as applied earlier. The 'effective moisture capacity' method (Janssen et al. 2009) is used instead. This technique presumes that the moisture mass in the stored objects is in equilibrium with the humidity of the indoor air. This allows integrating their moisture buffering effect by multiplying the moisture capacity of the indoor air with a correction term M:

$$M \frac{\partial M_{v,i}}{\partial t} = G_{v,in} - G_{v,out} - G_{buffer} \qquad (7)$$

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. The effect of including moisture buffering by the stored objects is shown in figure 7. The figure shows that the relative humidity drops to 45.5% on a summer day, when only the stored objects are accounted for (thus without the interaction with the building walls). The stored items play an important role in the stabilizing of the relative humidity, by absorbing and releasing moisture.

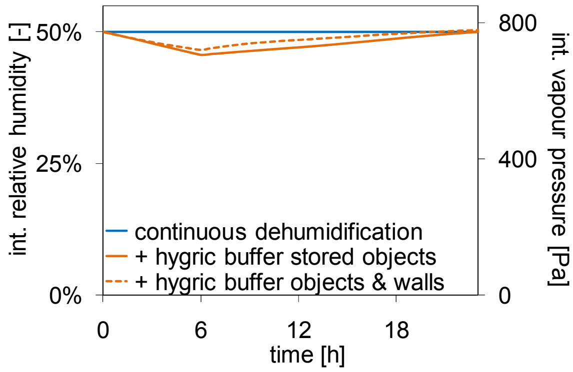

Figure 7 Indoor relative humidity simulated for the second day of July. The comparison shows the evolution of interior relative humidity resulting from continuous and concentrated dehumidification, with inclusion of hygric buffering by stored objects and unpainted walls.

When the interaction with unpainted building walls is added to the simulation, the interior relative humidity only drops to 46.5%. Additionally, it can be seen that the interaction with unpainted walls maintains humidities generally closer to the target 50 %RH. The difference between the lowest values for the two cases, respectively 45.6% and 46.5%, is significant compared to the reference level of 50 %RH. It is therefore recommendable not to paint the walls.

HIGHER BUILDING AIR TIGHTNESS

In the section above, it has been demonstrated that a concentrated dehumidification could be considered, since the resulting variations in indoor relative humidity remain restricted to a few percent. This building has an assumed air change rate of 0.04/h, the result of the limited air tightness of the building. The resultant infiltration of exterior air forms the main moisture source, and the key factor determining the response of the indoor humidity levels to concentrated dehumidification. Improved air tightness may then 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 shown in figure 8. The improved air tightness, and its reduction of the infiltrating moisture leads to a relative humidity drop of merely 0.5% (50% to 49.5%) due to concentrated dehumidification. This compares rather favourably to the earlier 3.5% drop. From figure 8 it can equally be noted that the interaction with the building walls (be they painted or not) becomes less important.

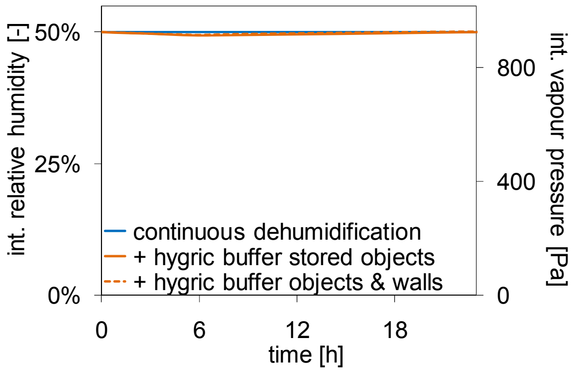

Figure 8 Results for a new air tight building Indoor relative humidity simulated for the second day of July. The comparison shows the evolution of interior relative humidity resulting from continuous and concentrated dehumidification, with inclusion of hygric buffering by stored objects and by unpainted walls.

RENEWABLE DEHUMIDIFICATION

The analysis above has demonstrated that the hygric inertia of the indoor air, building walls and stored objects is sufficient to allow for concentrated dehumidification during only a part of the day. For the rest of the day, the interior humidity can then be left free-running. For the building with an air change rate of 0.04/h, the resulting drop in the indoor relative humidity is limited to a few percent. For a more air tight building with a 0.01/h air change rate, the drop in relative humidity resulting from concentrated dehumidification is less than 1%. Once more, it should be kept in mind that many assumptions have been made in the quantifications above. Before actually implementing such concentrated dehumidification, an experimental verification of the suggested technique is highly recommended.

In the current building, measurements indicate that roughly 20.000 kWh are used to support the required continuous dehumidification. The concentrated dehumidification now allows for getting that energy from renewable sources, be they wind or sun. A key limitation of many renewable sources, their variable availability over time, can be overcome. For example, using concentrated dehumidification during the night takes advantage of cheaper electricity due to the lower cost of the excess energy. Currently Denmark produces 20% of its electricity from wind energy; the wind production is however not equally distributed over the day and the year. During the night or windy periods there will in many cases be an overproduction, which may now be used for dehumidification. This results in a contribution to a more stable consumption of electricity, a key factor of the effective utilization of wind energy.

Alternatively, one might consider the use of other types of renewable energy in order to support the dehumidification. In the current building in Vejle, the dehumidification employs absorption wheels, which are to be regenerated with electrically heated air. Instead solar collectors or heat pumps could be used to produce the hot air.

CONCLUSION

For optimal conservation 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 HVAC is installed to provide such stable indoor conditions. The resultantly significant energy and maintenance costs are currently motivating a paradigm change toward passive control. Passive control, via the thermal and hygric inertia of the building, is gaining a foothold in the museum conservation and building physical community.

In the paper (Christensen et al. 2010) the hygrothermal performance optimisation of a museum storage building, related to an existing storage centre in Vejle (Denmark), was studied. The results showed that the original promise of ‘a passively conditioned storage building was an illusion. The analysis also showed that dehumidification is the most economical option. To reduce the dehumidification load, only one strong solution exists: a more airtight building. The focus in the new design should therefore go to a construction method allowing for a very airtight building. The original design scored well on this issue, except for the wall-roof joints.

The purpose for this paper is to show that it is possible to reach the goal of using renewable energy for museum storage buildings by rethinking the strategy for the dehumidification design and in this way contribute to a $C0_2$ neutral environment. Year-round dehumidification is necessary to maintain acceptable interior humidity levels. The large interior mass of the storage (made up by stored objects and unpainted walls) would though allow concentrating the dehumidification during a part of the day, while leaving the humidity free-running during the remainder of the day. The large interior hygric inertia would limit the relative humidity variations to acceptable levels. This concept could be used to use cheap wind electricity during the night (where an excess of wind electricity is produced), or to couple solar collectors to absorption wheel dehumidifiers. Both measures would drastically reduce the dehumidification’s economic and ecologic costs and open up for the possibilities for using renewable energy and by this way reduce the $C0_2$ emission to the earth.

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NOMENCLATURE

A	moisture exchange surface area [m^2]
$G_{V,people}$	vapour production by people [kg/s]
$G_{V,dehum}$	vapour removal by dehumidification [kg/s]
$G_{v,in}$	moisture entering, from people and infiltration [kg/s]
$G_{v,out}$	moisture exiting, from exfiltration and dehumidification [kg/s]
M	correction term M, which is multiplyed on the moisture capacity of the indoor air $M_{v,i}$
$M_{v,i}$	moisture content of indoor air [kg]
n	air change per hour [h^{-1}]
$p_{v,b}$	representative vapour pressure of the buffer layer [Pa]
$p_{v,e}$	vapour pressure of the exterior air at t [Pa]
$p_{v,e}$	vapour pressure of the indoor air at t+Δt [Pa]
$p_{v,sat}(T_b)$	saturated vapour pressure at temperature [Pa]
R_V	gas constant of water vapour [J/kgK]
t:	current time instant [s]
t_p	period of boundary condition variation [s]
T_b	temperature of the buffer layer [K]
Δt	time step [s]
V	volume of the building [m^3]
β	convective surface vapour transfer coefficient [$2 \cdot 10^{-8}$ s/m]
δ	moisture permeability of buffer material [s]
ξ	moisture capacity of buffer material [kg/m^3]

Indices

t	at instant t
t+Δt	at instant t+Δt

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