A critical look at the use of HVAC systems in the museum environment

Edgar Neuhaus

Abstract

Complex heating, ventilation and air conditioning (HVAC) systems are often used in museums to optimise the indoor climate for preservation and visitors' comfort. In practice these systems regularly do not function according to their design specifications. As a result the indoor climate for preservation can be even worse than if the system were not used. For example, high daily relative humidity fluctuations can occur due to malfunctioning equipment or faulty control strategies; furthermore unexpectedly high energy use can occur due to too strict climate boundaries being pursued and mistakes made during the design phase. The functioning of a HVAC system should therefore not be trusted blindly but some level of caution should be taken. Monitoring indoor climate conditions independently from the HVAC system is essential.

Illustrated by various cases taken from Dutch practice, this paper tries to raise awareness among collection managers, curators, restorers and other museum professionals. The most frequently encountered problems with HVAC systems in the museum environment are described and general recommendations are given to avoid, detect and resolve these problems. This paper is not intended to discourage the use of complex HVAC systems since when designed, controlled and maintained properly, these systems can offer a great contribution to the preservation of cultural heritage.

Introduction

Preventive conservation can be described as a process that seeks to prevent, reduce or mitigate the effects of factors that threaten the continued survival of collections. An incorrect relative humidity (RH) or temperature, high levels of dust and gaseous pollution are some of these threatening factors that can be reduced by using mechanical systems. Inappropriate values of temperature and RH are often less dramatic than, for example, the risk of fire or theft, but nonetheless pose a serious problem for the conservation of heritage. The approximately 800 registered museums in the Netherlands, of which around 90 % are housed in historic buildings, are therefore often equipped with air-handling units (AHUs).

In cases with high visitor numbers, often vast HVAC systems are needed primarily to bring in enough fresh air for visitors' health and comfort. These are typically museums with a highly-prized collection or historic house museums with a small air volume. Due to financial reasons, often a maximum annual amount of visitors is desirable, so large HVAC-systems are installed to provide enough ventilation rather than limiting the amount of visitors.

Besides providing fresh air and thermal comfort for visitors and staff, these machines are intended to control environmental influences for preventive conservation. Figure 1 shows a simplified representation of how a typical AHU in a museum works. The building management system (BMS), a computer-based control system, controls the mechanical components of the AHU and is connected to sensors in the exhibition space and sensors in the AHU. Depending on the conditions of the outside air and return air and what the desired inlet condition is, the BMS decides whether the supply air should be cooled, heated, humidified or dehumidified. Additionally the air is filtered in the AHU. It has to be noted that more and finer filter packages lead to a substantially higher energy use because of a greater pressure loss which has to be compensated by the supply fan.

From the 1980s onwards confidence in mechanical system began to grow and the feeling prevailed that all climate risks could be excluded. Controlling the RH as tightly as possible was considered the best course. Guidelines with a strict allowable bandwidth for RH were based on the mechanical limitations of the HVAC system rather than on collection needs. These tight boundaries for temperature and RH often resulted in the assembly of vast and energy-guzzling equipment.

It is only relatively recently that scientific research has provided a basis for determining appropriate values for the museum climate, particularly the range in which temperature and RH can be safely allowed to vary [1, 2, 3]. This more object-oriented approach, based on chemical, physical and mechanical properties of materials, is now becoming more widely acknowledged and more rational environmental standards or guidelines are beginning to emerge. The decline of the financial climate, more scientific information becoming accessible and the reduction of reliance on fossil fuels ('going green'), have certainly played a role in this transition.

However, countries in western Europe still tend to focus on optimising the indoor climate primarily by active means, meaning mechanical systems are favoured over, for example, architectural features. Passive means to optimise the indoor climate, for example, building physical measures, can be considered as more durable and reliable but are often disregarded. There may be various reasons for this situation, for example, it may be illegal to change the aesthetics of the protected historical building, or because the proposed measures do not comply with the architect's vision. Mechanical systems are then needed to compensate for the lack of proper sun shading or insulation, or to remove the great

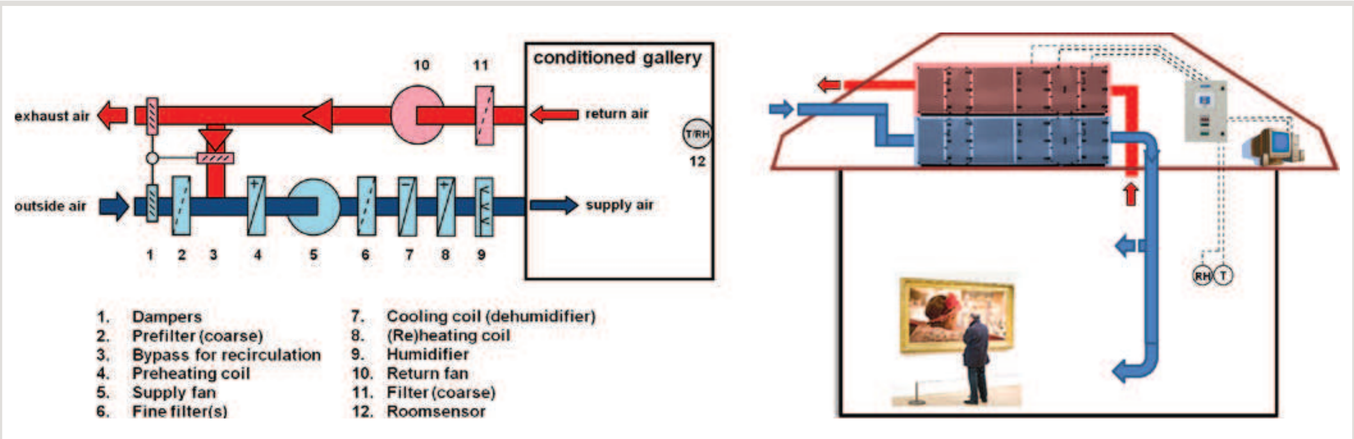

Figure 1. A simplified representation of how an air-handling unit in a museum works. The picture on the left shows a schematic view of the main components. The picture on the right shows a museum with an AHU and connected ducts. The AHU is controlled by the computer-based building management system

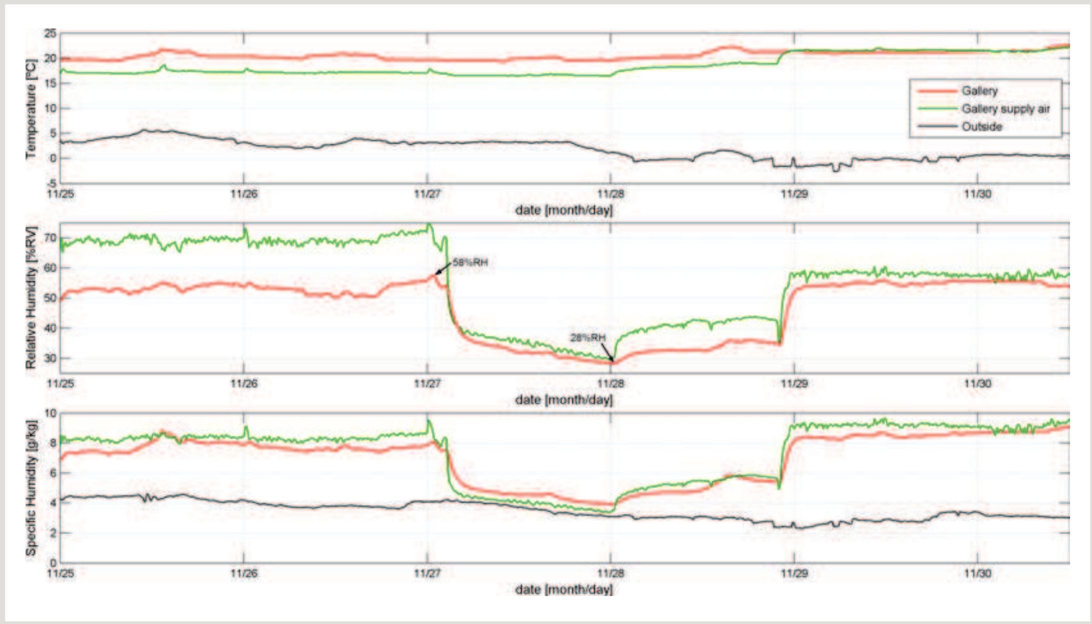

Figure 2. These graphs show the effect of a malfunctioning humidifying system during the heating season: RH in the conditioned exhibition space drops about 30 % within 24 hours. Note: if the HVAC's temperature and RH set-point were to be seasonally adjusted, e.g. 22 °C/55 % RH during summer and 18 °C/45 % RH during winter, the drop would be about 17 %

heat load due to large glass facades in newly built architecturally-sound museums.

In practice, installed HVAC systems often do not function properly, leading to unnecessarily high energy consumption and maintenance costs. In some museums the climate can even be more disrupted and unstable than without having a climate system, posing a threat to the conservation of artefacts on display and the historic building structure itself.

Methods

In various museums equipped with an AHU and facing climatic problems, research is performed in order to optimise climate conditions for preventive conservation. This research typically consists of three steps. The first step is collecting climate data (temperature and RH) of indoor air, outdoor air and supply air for a minimum of a several weeks. The shortcomings of the equipment can often be made visible with this data by simply calculating and comparing the specific humidity of outdoor air, indoor air and supply air.

The next step is to analyse the building and HVAC characteristics. During a global inspection, information is gained about, for example, the level of insulation, level of airtightness, orientation of the exhibition spaces, type of air distribution, type of cooling system and level of air recirculation. The collected climate data can be better interpreted with this additional information. In addition, the functioning and configuration of hardware and control systems are inspected, including important field sensors. The last step consists of analysing the collected data and trying to attribute the shortcomings detected to specific components of the system.

Common problems

Based on experiences from Dutch practice collected over the past five years, the three most common problems are described and analysed here.

HVAC-system malfunctions, causing a large disruption in RH

If one of the components of a climate system malfunctions, temperature and RH control can easily be disrupted. For this observation we need to distinguish two types of malfunctions.

The first type can be described as an acute but usually short-term malfunction, for example, the malfunctioning of a steam humidifier in an AHU that conditions 100 % outside air. During periods of frost outside, air can contain very little moisture. RH fluctuations of 25 % or more within a few hours can occur when outside air is only heated, filtered and then supplied to a room (Figure 2).

The malfunction shown in figure 2 was relatively quickly remedied. In this case the failure was instantly detected due to built-in alarm functions in the building management system and the adequate response of the people responsible. However, this situation could have had less climatic impact if two humidifiers had been installed which could be switched over automatically by the building management system for runtime balance and during failure mode. Redundancy, the duplication of critical components for increased reliability, is therefore essential for HVAC-systems in museums with climate-sensitive collection. This concept also includes keeping spare parts of failure-prone components on site. Examples of such components are fan belts and steam cylinders for humidifiers. Furthermore it should be noted that if the set-point for temperature and RH had been seasonally adjusted, the difference between specific humidity of indoor air and outdoor air in this particular case would have been less, resulting in a smaller RH fluctuation in the event of a malfunction.

Large disruptions of the museum climate can also occur during maintenance. Annual periodic maintenance should therefore preferably be scheduled during the intermediate seasons, in which the difference between the specific humidity of the inside and outside air is relatively small. During these seasons the specific humidity of the outside air in the Netherlands ranges between 5 to 10 g/kg in general.

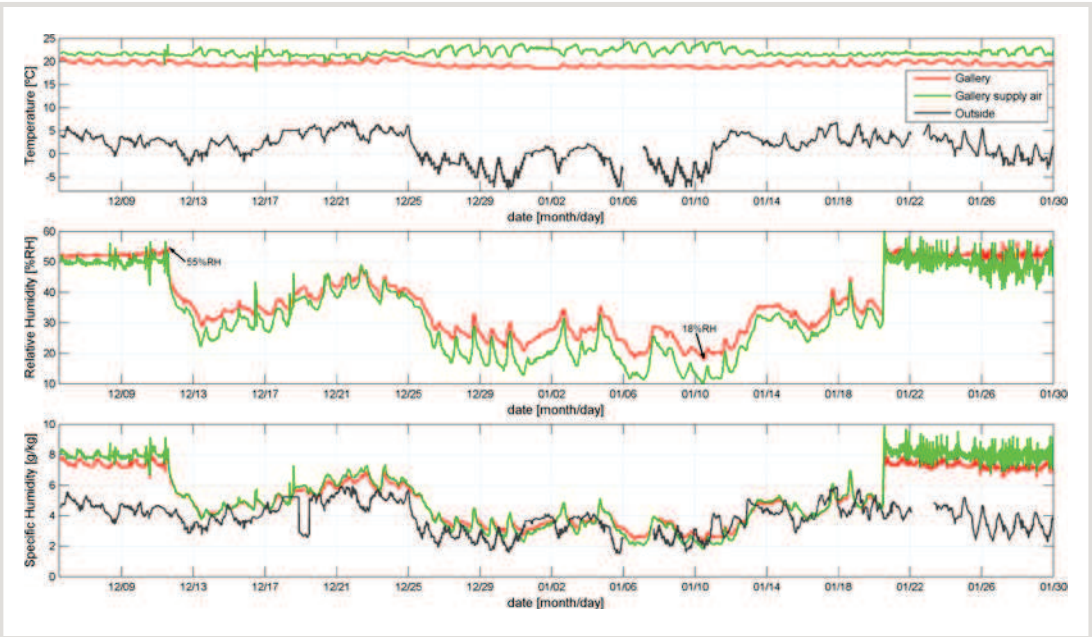

Figure 3. An example of a long-term RH drop due to malfunction of the humidification system which was not detected instantly, recorded in a Dutch museum. RH in the gallery drops from 50 % down to values as low as 17 %. It took 39 days before the system was eventually fully operational and the room RH was restored

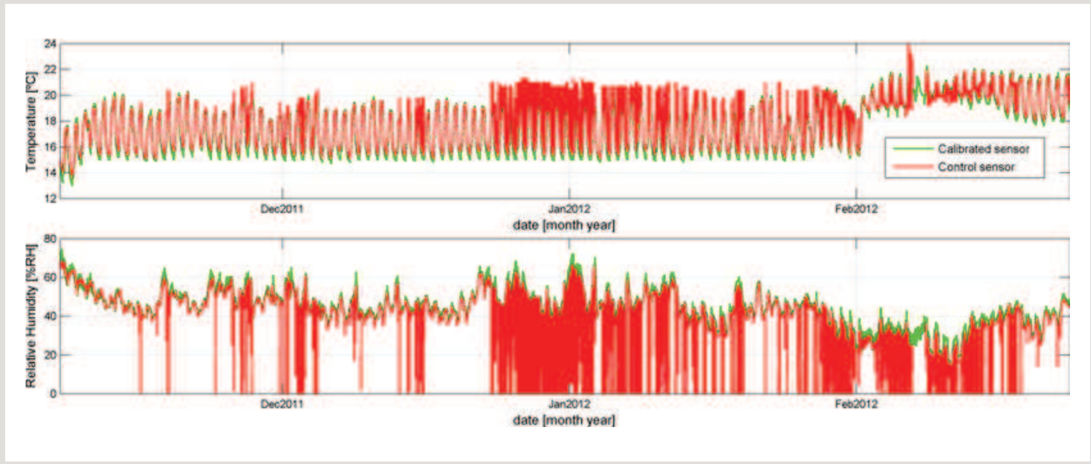

Figure 4. Example of data that are registered by a faulty control sensor (red line) and sent to the BMS. Data obtained with a calibrated stand-alone sensor, which was placed near the control sensor, are plotted in green

The second type of malfunction can be described as a long-term erroneous functioning of the system. This can mostly be attributed to ineffective monitoring of the functioning of the system or ineffective monitoring of the indoor climate conditions by incompetent staff or maintenance firms. Long-term malfunctioning is best illustrated by the unfortunate event that happened in the storage facility of the Ancient Art Museum in Brussels in 2009. During the winter season, the humidification system for the museum storage area malfunctioned, resulting in a RH drop which was only discovered after 55 days. By that time hundreds of the 842 stored paintings were damaged, mostly suffering from problems with the paint layer, with estimated restoration costs of 1 million Euros [4]. Figure 3 shows the indoor climate conditions in an exhibition space for a similar situation, recorded in 2009 in a Dutch museum. Apart from a relatively long period in which hygroscopic collections will desorb moisture, two critical RH fluctuations occur; once when the humidifier stops working and once when the humidifier is repaired. In this case it might be better to slowly rebuild the moisture level to the set RH, instead of 100 % capacity in a very short time.

Another issue that can lead to long-term incorrect functioning of an AHU is the result of defective room sensors or control sensors. These sensors usually do not automatically generate an alarm in case of breakdown or faulty behaviour, and in the best case are inspected and calibrated once a year. Figure 4 shows data sent to the BMS by a faulty control sensor, compared with data collected with a calibrated stand-alone sensor. The faulty data led directly to an incorrect functioning of the AHU. Important system sensors therefore should be checked regularly. It is highly recommended that data are collected with an independent monitoring system where sensors are also placed near to the system's control sensors.

Figure 5 shows a disrupted museum climate caused by errors in the BMS. In this particular case, erroneous and unstable control signals led to an incorrect functioning of AHU components and an unstable room temperature and RH. Due to errors, the set-point of inlet temperature was locked and the control of the cooler was unstable. The situation was restored by replacing a defective circuit board in the BMS. These problems can often only be discovered and resolved by in-depth inspection of the system, analysing control systems and configuration of the BMS.

Incorrect system selection or design

An incorrect system selection can be observed in various museums. Systems unsuitable for the museum environment can create stable climate conditions close to the room sensor, but with very unstable conditions in the vicinity of collection objects, or they can cause large hygrothermal stratification [5, 6, 7]. Examples of this are systems where supply air is not being fully mixed in the room or inlet grilles are inconveniently positioned. Figure 6 left shows a thermal image of a gallery where the supply of conditioned air takes place at floor level, causing warming up and drying of paintings which are hung directly above the floor grilles. Figure 6 right shows an exhibition space with a radiant floor heating system. During the heating season the floor temperature can be 5 °C warmer than the average room air temperature. This means that if the space is conditioned to e.g. 20 °C/50 % RH, objects placed on the floor will experience a RH of about 37 % or even lower near the contact area and could possibly suffer damage due to desiccation.

The position of the control sensors in the exhibition room is of great importance as this will determine the condition of the supply air. The best position of the control sensors is close to climate-sensitive collection objects. It is regularly observed that control sensors are positioned in the return air duct, sometimes far away from the exhibition room and very near to the AHU. Temperature and RH in a duct 20 or 30 metres away from the exhibition room, however, can differ from room conditions, thus a deviation is created, particularly in systems with a variable air-flow.

Unrealistic and unnecessarily strict demands

The third problem encountered with HVAC-systems in the museum environment is the result of an overly strict set bandwidth for temperature and RH. Historic buildings are often poorly insulated

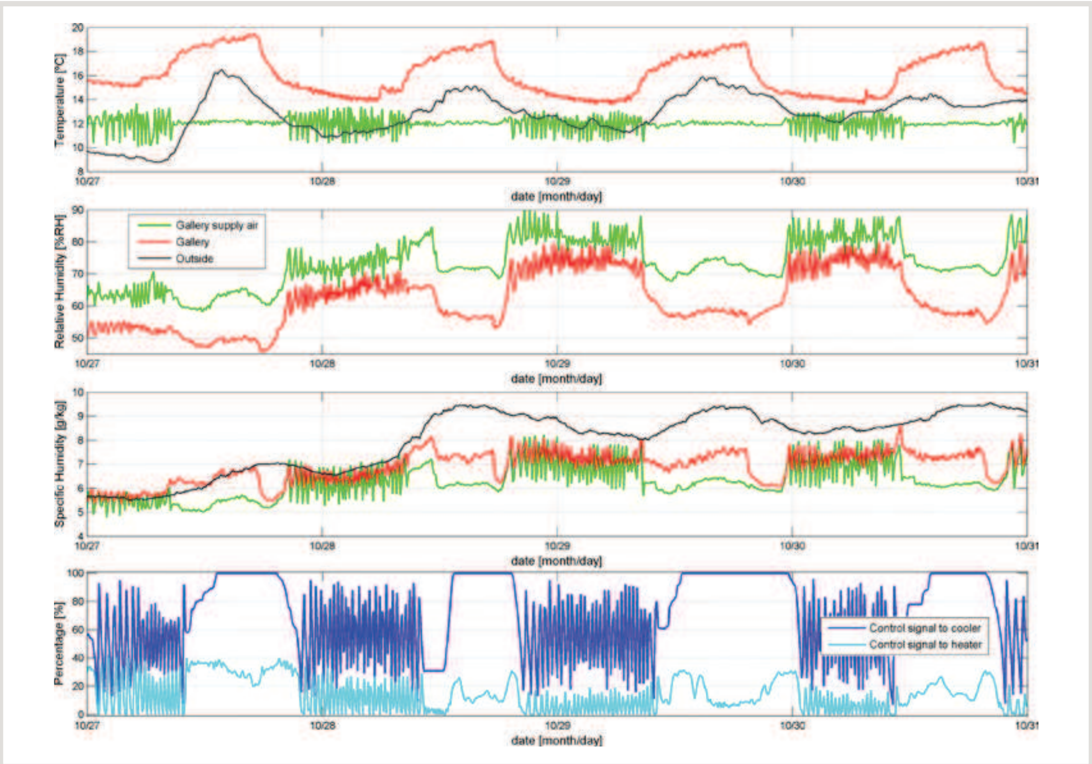

Figure 5. In this particular case erroneous control signals were sent to the AHU by the BMS due to a defective circuit board

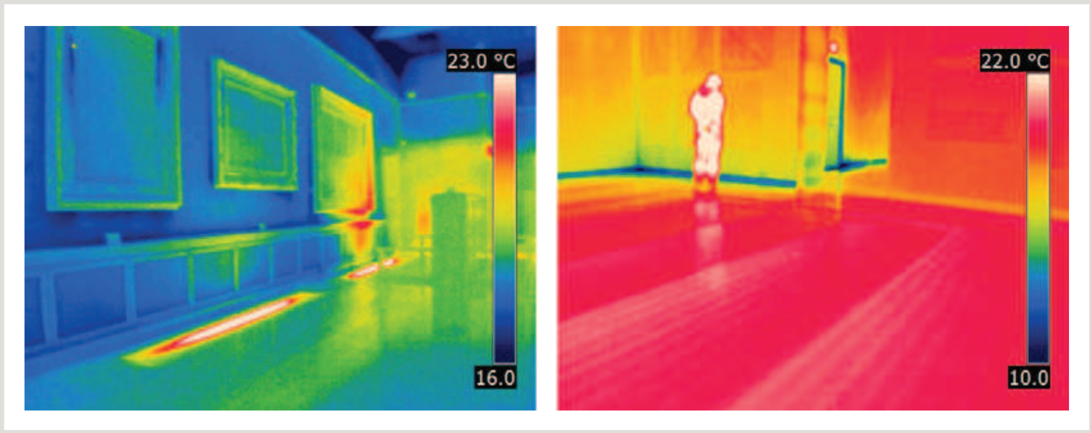

Figure 6. The left thermal image shows an exhibition space where conditioned air is being supplied through floor grilles which are located about 0.8 metres under the paintings. Supply air is therefore not able to fully mix and paintings can be exposed to detrimentally high or low temperature and RH and large climatic fluctuations. The right thermal image shows a museum with a radiant floor heating system. Whilst RH near the control sensor can be 50 %, RH at floor level can be as low as 37 %

and quite leaky. When applying tight RH control in such buildings problems occur mostly during the winter. It can be commonly observed that there is heavy condensation on single glass panes, leading to leakage in the exhibition room, mould growth and rotting of wooden window frames. While spatial RH can be perfectly level at 50 %, RH near cold walls can be much higher. Figure 7 shows a thermal image of a painting against an uninsulated wall during winter. Whilst RH in the room is about 50 %, RH behind the painting is well over 75 %. In this case, the collection could be at risk due to possible long-term very high RH in winter [8]. During periods with very low external temperatures, in some cases condensed water can be observed running down the interior face of exterior walls from behind paintings. This problem can be significantly reduced or even avoided by just slightly lowering the set value for the room temperature and the set RH. Whereas a set point of 20 °C/50 % RH has a dew point of 9.3 °C, a set point of 18 °C/45 % RH has a dew point of 5.9 °C. Therefore, in air-conditioned poorly-insulated buildings collection should not be placed against outside walls, or spacers should be used to keep an air space between walls and paintings.

How these problems occur and can be avoided

HVAC-systems in the museum environment are different from systems in office buildings. Here 24-hour operation is required and systems therefore need to be robust and reliable. Spare vital components, such as humidifiers, should be kept in reserve, so that in case of malfunctioning or maintenance disruption of climate conditions will be limited. Air distribution should be well mixed, to avoid stratification and to promote homogeneous climate conditions. Depending on possible sources of pollution in the building, as much air as possible should be recirculated and outside air should be the minimum amount required to provide fresh air for visitors. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) handbook [7] describes the various systems that are applicable for controlling temperature, RH and airborne pollutants in the museum environment in more detail.

Control of the system should be incorporated in a building management system which is, to some level, accessible by the user. Data from (room) sensors and control signals to the systems components should be logged by the BMS. Data that should be visible to the user at any time are: RH in the exhibition spaces and the temperature and specific humidity of outdoor air, supply air

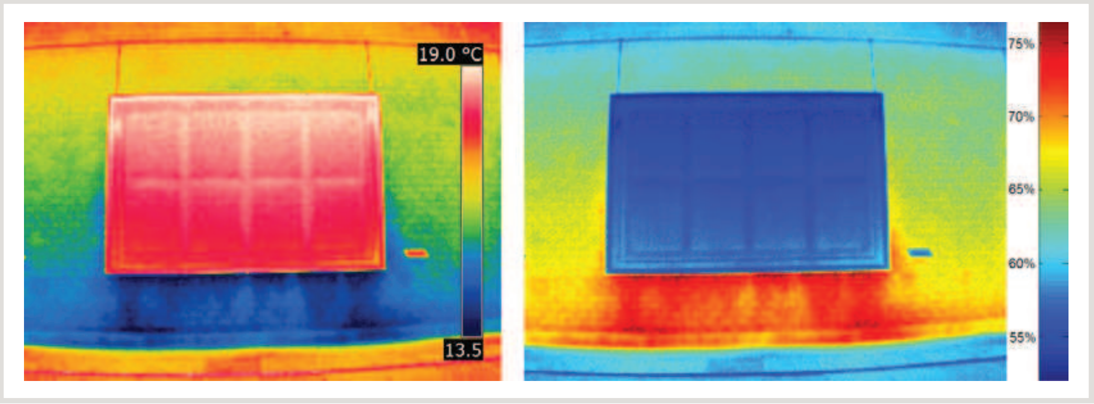

Figure 7. Example of a seventeenth-century painting hung on an un-insulated external wall in a museum that is conditioned to 20 °C and 50 % RH. The thermal image shown left, is taken during wintertime. Clearly visible is the cooler surface under the painting. The right image shows a hygrograph with the calculated surface RH of the same situation. It can be expected that the RH behind the painting is well over 75 %

and room air. Registered temperature and RH should be coupled to an automated alarm function, so that in the case of specific values exceeding or undershooting a set bandwidth, an alarm, via email or text message, is generated to the museum's facility manager or directly to the maintenance company.

As well as monitoring via the BMS, it is essential to monitor indoor climate conditions with a stand-alone wireless monitoring system that is also capable of generating alarms if conditions fall beyond the desired boundaries.

The problems as described above are often also caused by the fact that HVAC designers primarily focus on thermal comfort (temperature-control) and often have limited knowledge or experience with controlling RH. Collection managers, conservators and facility managers often lack a (basic) knowledge of building physics and HVAC systems and are therefore not always adequately able to adjust proposed HVAC plans. An interdisciplinary collaboration with the appropriate specialists from the early stages of a renovation project or the new build of a museum is essential.

Conclusion

This paper highlights common problems when using HVAC-systems in the museum environment. The Dutch experience indicates that expensive HVAC systems are no guarantee for having optimal climate conditions for preventive conservation. Malfunctioning equipment or faultily designed systems can cause heavily disrupted climate conditions near collections and can even decrease the lifetime for exposed or stored objects. Malfunctions can occur due to an erroneous control strategy or defects in hardware. In the museum environment critical HVAC-components should be kept in reserve, and the system should have a comprehensive self-check and alarm function for detecting malfunctioning components or sensors. Indoor climate conditions should be monitored constantly, not only by the building management system but also by an independent monitoring system, which automatically generates alarms if conditions are out of range. Some types of HVAC-systems might successfully be applied in settings other than museums or storage facilities, but might not work when RH control and homogeneous indoor conditions have precedence over temperature control.

A significant amount of attention should be given to optimising the physical structures before bringing in mechanical systems. Building physical measures to optimise the indoor climate can be considered as being more durable and reliable and preferable to mechanical systems. An example of this is effective sun shading or adequate thermal insulation. Mechanical systems should be regarded as a last resort.

For new-build museums or storage facilities the design phase is critical to achieve an optimal indoor climate. An interdisciplinary design team consisting of an architect, engineers, conservators, collection managers and security staff should be carefully selected at the very start of the project so the right knowledge and expertise are brought together.

Recent literature shows that the indoor climate in most museums is unnecessarily tightly controlled. When a museum or storage facility is newly built or being renovated the collection should be thoroughly assessed first. What climate boundaries and fluctuations are actually safe for this specific collection? For most objects RH fluctuations do not pose a large risk, as long as they are gradual, within certain boundaries, and at values where chemical and biological degradation are not imminent. Sensitive objects could possibly be placed in display cases in which the local environment can be more closely controlled, rather than conditioning the whole building's air volume.

Unfortunately, museums are still being built or renovated with a prescribed HVAC system designed to maintain RH in the exhibition space at 50 % plus or minus 1.5 % the whole year round, without taking account of the fact that standard measurement equipment has uncertainties greater than the specified range. HVAC systems can be designed on a smaller scale if temperature and RH are allowed to vary during the year, saving substantial costs in terms of equipment, energy, personnel and maintenance.

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Author

Edgar Neuhaus is a private consultant specialising in optimising the museum climate for preventive conservation. Email: e.neuhaus@physitec.nl

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