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PREVENTIVE CONSERVATION

When an HVAC design becomes reality: Investigating the impact of floor heating on the indoor climate risks in a contemporary art museum

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ABSTRACT

The consequences of installing underfloor heating in a contemporary art museum for the presentation and conservation of artworks are addressed in this paper. The subsequent relative humidity (RH) and temperature gradients are identified and analyzed. The research results show that above floor level, a vertical temperature gradient occurs of about 4°C in the first 0.1 meter, leading to lower RH readings at floor level. Objects placed on a heated floor cause thermal shielding. This results in RH gradients of up to 17% between lower and upper areas of objects placed on floors with underfloor heating. These large gradients can lead to accelerated degradation of climate-sensitive objects if no further measures are taken. Recommendations resulting from the technical research are described and discussed.

INTRODUCTION

In the renovation plans for the Stedelijk Museum Amsterdam's (SMA) museum building, heating, ventilation, and air conditioning systems (HVAC) were planned in order to ensure a stable climate for the preservation of the museum's collection and objects on loan.

The SMA is the custodian of the collections and of the museum building, while the City of Amsterdam is their owner. The City of Amsterdam's Project Management Bureau (PMB) developed a program of requirements with input from specialized museum departmental staff. The PMB commissioned a consultancy firm with experience in HVAC systems for cultural institutions to design the system. The PMB relied mainly on the HVAC consultancy firm's experience for the development of the HVAC system.

The general relative humidity (RH) and temperature criteria were set out in the program of requirements (Ankersmit 2009, ASHRAE 2011): winter temperature: 16°C–20°C (18°C ± 2°C); summer temperature: 18°C–22°C (20°C ± 2°C); year round RH: 50% ± 5%. Furthermore, one of the requirements was uniformity of temperature and RH in the exhibition spaces. In order to satisfy this specific requirement, and at the point when the design brief was translated into the technical specifications of the HVAC, underfloor heating was included as an intrinsic part of the HVAC design, with 70% of the heating capacity coming from the air handling system and 30% from the underfloor heating. The consultancy firm estimated that, as air was being supplied at ceiling level and extracted at floor level, the air flow would pass over a heated floor which would result in homogeneous hygrothermal conditions in the exhibition spaces. As a result of a complex design process, in which museum staff were not permanently involved, and as a result of the above-mentioned technical decisions, the museum ended up installing hydronic underfloor heating in all of its exhibition spaces (a total of 6490 m²).

The underfloor heating could not be regulated by exhibition room. It was to function as a basic heating system with a surface temperature of about 25°C. Moreover, the system would not work constantly, but would turn on or off sporadically and automatically. At the time, it was unclear what "sporadically" meant. It was assumed that during warm seasons (April–September), the floor heating would turn on sporadically, while during colder seasons (October–March), it would operate almost continuously.

The installation of underfloor heating in a contemporary art museum is uncommon. Literature and studies concerning the influence of floor heating on contemporary art collections are scarce. Important repercussions for the presentation and conservation of the museum's collections were to be expected. Objects are frequently placed directly on the floor, whether it be from an aesthetic point of view or due to the artist's requirement, or even due to the nature of the work which may need to be securely fixed into the floor.

Parallel to the HVAC design stage, an interior designer was commissioned by the museum to develop a new display case for the refurbished and extended museum. Glass and metal were to be used as construction materials. The case design was unique in that it contained no shelving unit at its base. There would therefore be no protective physical barrier between the floor and the lower shelving, now located higher up in the display case. The result of this design choice was that objects in the display case could be exposed to radiant heat, RH, and temperature gradients due to the presence of the underfloor heating.

In order to be able to determine the actual risks to the collections, the museum deemed it essential to investigate the possible short- and long-term impact of the underfloor heating on the collections and on the microclimates not only within the building, but also on collections presented in the new display cases.

The collection care department of the SMA consequently commissioned the Netherlands Cultural Heritage Agency and Eindhoven University of Technology, assisted by the engineering company Physitec, to carry out scientific research regarding a number of aspects related to the installation of underfloor heating in the museum's exhibition spaces. The museum's main queries were as follows:

- What would be the actual impact of radiant heat on objects when installed directly on the floor or on low plinths?
- What would be the influence of the underfloor heating on the climate within the newly designed showcases and thereby on the presented objects?
- Would dust displacement and deposit within and outside the showcases be expected to increase due to convection caused by the underfloor heating?

Furthermore, it was asked that recommendations concerning mitigation strategies to reduce the risks to the collection due to the presence of underfloor heating be provided.

Based on the museum's above-mentioned concerns, the following technical research objectives were formulated:

1 determination of the thermal stratification at the surface and around objects placed directly on the floor

2 determination of the hygrothermal gradients inside and outside a sealed and unsealed showcase

3 determination of the effect of the underfloor heating on the air exchange rate (AER) of the newly designed showcase when both sealed and unsealed.

Methodology

The research was conducted in a climate chamber with the RH set at 50% and the temperature at 20°C (with a variation of 0.2°C) in order to simulate as closely as possible the expected climate conditions in the finished building.

For the experimental setup (see Figure1), a floor with underfloor heating (2.5 × 1.5 m^2) was constructed using the same materials – wooden parquet on concrete – as was planned for the future museum building. The test floor had a limited surface area (about 3.75 m^2) and consisted of an electrical underfloor heating system adjusted to achieve a stable surface temperature of about 25°C with a fluctuation of 0.5°C, as in the manufacturer's specifications.

In the exhibition rooms, the larger floor area would result in more thermal radiation being emitted and captured by the objects on display. It can therefore be concluded that the objects placed on the floor, the glass surfaces of the display cases, and thus the volume within the display cases would be subjected to more warmth under real-life conditions.

Several dummy objects made from a variety of materials were placed on the floor inside and outside the case. Using an FLIR S65 HS infrared camera, thermal images of the dummy objects were made in order to determine the heating pattern of the floor and temperature differences at the objects' surfaces.

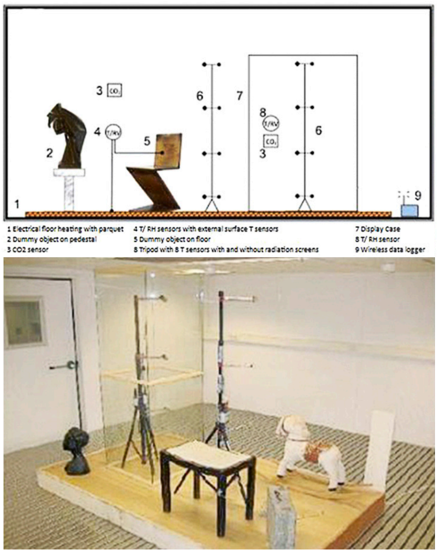


Figure 1
Top: schematic presentation of the experimental setup. Bottom: real-time setup in the climate chamber

A prototype of the display case, then still in its design phase, was made according to the case design specifications. The dimensions of the prototype were 1.85 × 0.6 × 0.6 m^3 (H × W × D) resulting in a volume of about 0.65 m^3. As the metal frame was not yet in production at the time, a wooden frame, with a profile very similar to the original design, was used and subsequently covered with metal tape. The display case was composed of nine separate glass plates (5 mm in thickness) and three wooden profiles into which the glass plates slotted. This resulted in a display case with three sections: a lower, middle, and upper section. As in the original design, no base shelving was placed in the case; the lower part of the display case was therefore in open connection with the heated floor. All joints and gaps in the display case were sealed with aluminum tape to study the temperature gradient in the showcase.

Hygrothermal stratification was measured by combined RH/temperature sensors attached to tripods. The air temperature was measured at four different levels inside and outside the display case: at 0.1, 0.6, 1.1 and 1.6 meters above the ground. The temperature sensors were fitted with radiation screens so that the air temperature could be measured as accurately as possible. In order to determine the AER of the show case, a CO_2 sensor was placed inside the case. During the nine-hour test period, the CO_2 sensor in the display case was switched off, no exterior or interior light sources were used, and no air disturbances (such as physical movement) took place. The temperature and RH were measured at one specific location inside and outside the case in order to calculate the specific humidity (g/kg). Using the calculated specific humidity and temperature readings, the RH was calculated for the different levels.

The AER in the sealed and unsealed prototype display case was determined by CO_2 tracer gas detection, using a Vaisala GMD21CO_2 sensor. The aim of this test was to gain insight into the influence of the underfloor heating on the AER. The infrared CO_2 sensor emitted some heat, resulting in a small temperature increase of approximately 0.2°C in the display case.

RESULTS AND DISCUSSION

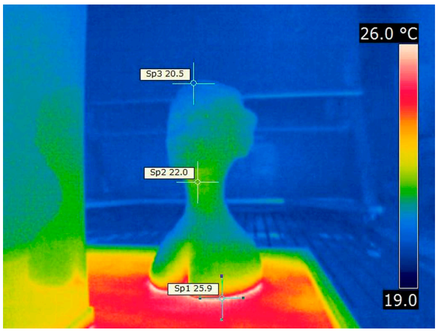
Hygrothermal stratification around the objects placed directly on the floor and at their surface

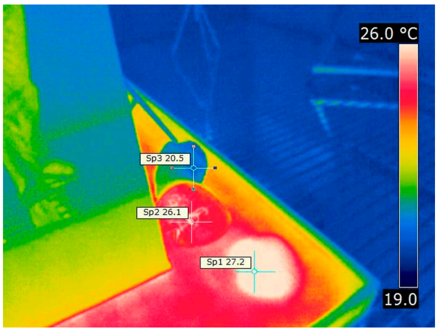
Figure 2 shows an infrared image of a dummy artwork (polystyrene covered with a layer of modeling wax) placed directly on the floor. The surface temperature of the floor was 25°C. The image clearly shows a temperature gradient over the object of 20°C at the top and approximately 26°C at the bottom. It can also be noted that the object was locally exposed to heat radiation of up to 22°C, for example in the neck area.

When the object was turned on its side (Figure 3), a clear temperature increase at the contact surface was visible; the surface temperature of the floor where the bust had been placed was then approximately 27°C. The contact temperature under the bust was higher than the overall surface temperature of the floor. This was caused by the thermal insulation of the object, which prevented the local emission of radiation and convective cooling.

The local RH was calculated using the local temperatures (Schellen 2002) and calculated specific humidity, assuming that the specific humidity in the room was uniformly distributed. The thermal image of the object was then translated into a hygrogram.

The hygrogram in Figure 4 shows that the surface RH of the object placed directly on the floor was approximately 33% near the floor and 50% near the top. This produced a visible RH difference of about 17% between the lower and upper part of the object. This kind of gradient is considered to be a significant risk for hygroscopic objects such as wood. Local heating will lead to local drying of hygroscopic materials due to low surface RH. Due to local drying, stresses are expected to form within the objects which could lead to (local) cracking, warping, or splitting. Furthermore, due to the higher local temperatures, accelerated chemical degradation is expected, which presents a potential threat to chemically instable objects.





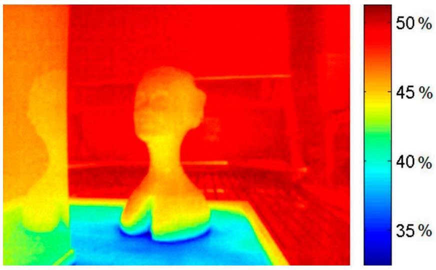


Figure 2
Thermal image of a dummy object placed directly on the heated floor

Figure 3
Thermal image of a dummy object placed directly on the heated floor shortly after it has been turned on its side

Figure 4
Hygrogram of the bust, calculated from the thermograph in Figure 2

Hygrothermal gradients inside and outside the sealed and unsealed showcase

The thermal gradients inside and outside the display case were measured in four different situations: floor heating on and off, and display case sealed and unsealed.

The first measurement results (heating off and case unsealed) showed temperature gradients that were of roughly the same magnitude outside as inside the unsealed display case. Obviously, switching on the underfloor heating resulted in a temperature gradient, both outside (see Figure 5) and inside the unsealed display case (Figure 6). The lowest sensor outside the display case (0.1 m above the floor) showed a temperature of approximately

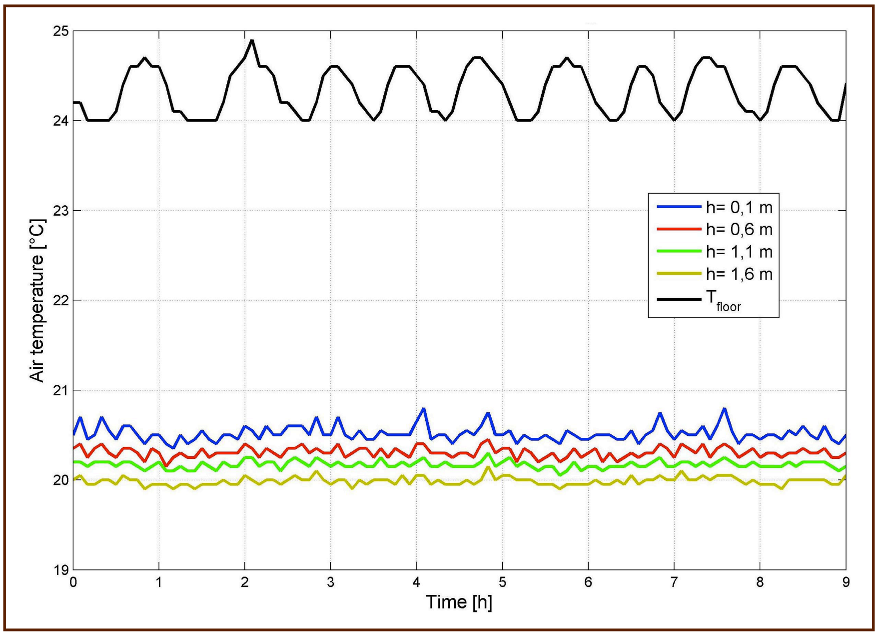


Figure 5
Temperature profiles at different heights outside the showcase with heating on

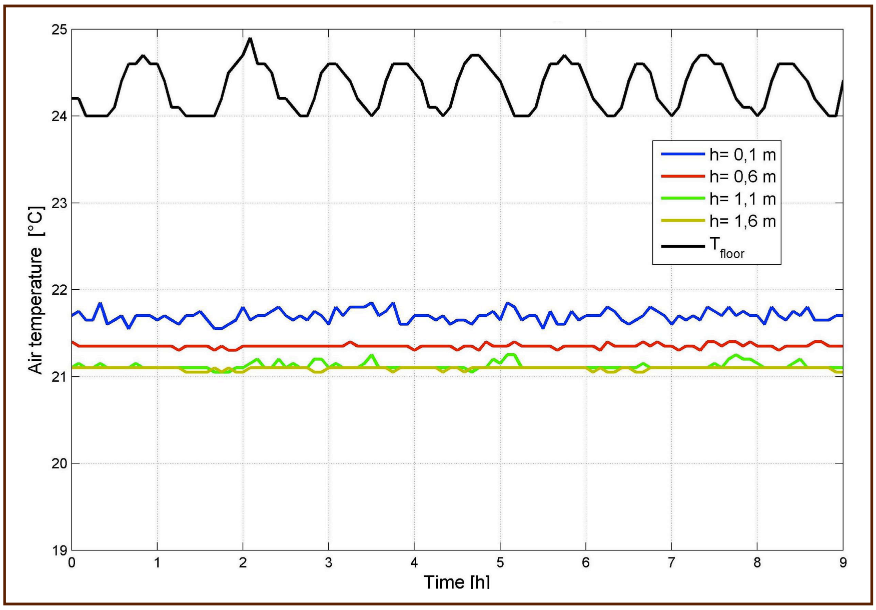


Figure 6
Temperature at different heights in the unsealed display case with heating on

20.5°C, while the sensor at the same height inside the display case showed a temperature of approximately 21.7°C. The highest sensor (1.6 m) outside the display case showed approximately 20.0°C and inside approximately 21.1°C. Generally, the temperature inside the unsealed display case was about 1°C higher than outside.

Sealing the display case did not change the location or shape of the temperature gradient; this can be clearly seen when comparing the black and red line and the green and blue curve in Figure 7. Due to the underfloor heating, the highest temperature and largest temperature gradient in the case was measured closest to floor level (0.1 m above the floor). Above 1.1 m, air conditions were practically uniform. This also applied to the measurements taken outside the showcase.

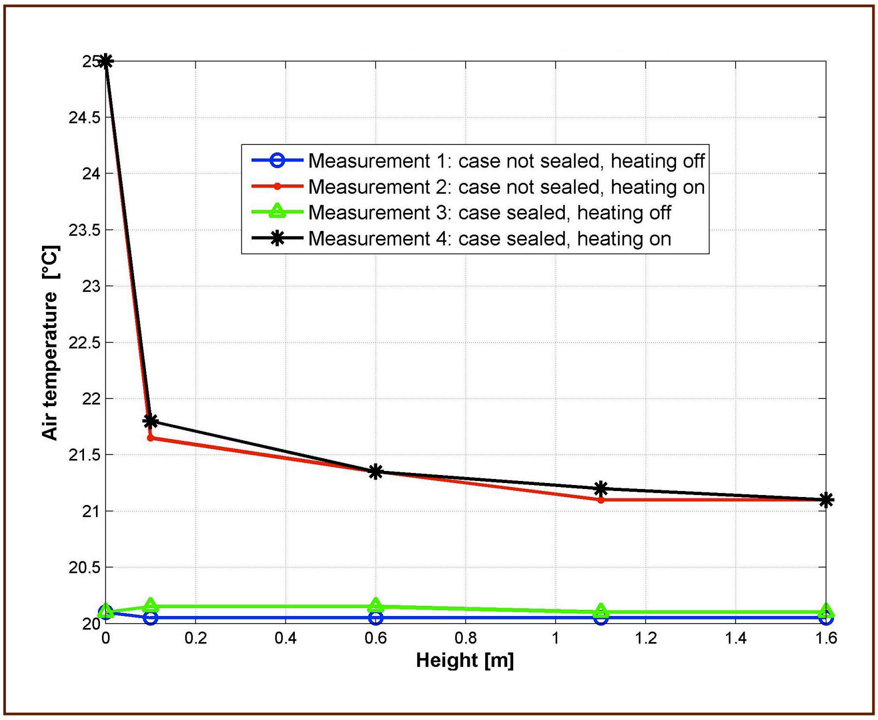


Figure 7
Air temperature profiles inside the showcase for the four experimental situations (Table 1)

From the temperature readings presented in Figure 8, the RH gradients were calculated. The RH gradient over the first 0.1 m was clearly the highest, at about 8% RH. At 1.1 m above the floor, the climate conditions are more or less uniform.

Figure 8
Left: Yayoi Kusama's *Aggregation: One Thousand Boats Show*; middle: Gerrit Rietveld's *Zigzag stool*; right: Carl André's *Bloody Angle*

Air exchange rate of the newly designed showcase

The AER of the display case was measured in four different situations: floor heating switched on and off, and display case sealed and unsealed.

Table 1 shows the results of these experiments. As expected, it can be clearly seen that sealing the display case significantly reduced the AER. In this experiment, the AER decreased from 2.01 changes per day ["moderately sealed" according to the literature (Raphael and Davis 1999)] to 0.17 changes per day ["well sealed" according to the literature (ibid.)] after sealing. Switching on the floor heating resulted in an increase in the AER of the unsealed display case by a factor of about 3, from 2.01 to 5.99 changes per day. In the case of the more airtight display case, underfloor heating did not significantly influence the AER.

Table 1
AER measurements of a sealed and unsealed display case with the floor heating on and off

	AER [day^{-1}]
1. Floor heating off, display unsealed	2,01
2. Floor heating on, display unsealed	5,99
3. Floor heating off, display sealed	0,17
4. Floor heating on, display sealed	0,19

CONCLUSIONS AND RECOMMENDATIONS

With the underfloor heating on, the most significant warming of air occurred in the first 0.1 m above floor level. In this air layer, the temperature difference was about 4°C, with a corresponding RH difference of about 9%. At 1.1 m and higher, the climate was considered to be uniform. The inside of the display case was slightly warmer (approximately 2°C) than the outside environment.

As a result of this temperature difference, the RH in the display case under actual museum conditions would be about 44%, while the RH in the exhibition room was to be conditioned at 50%. It should be noted that inside the case, the temperature gradient would also result in an RH gradient. In practice, the display case climate would be influenced additionally by external heat sources, such as lighting. The degree of air tightness of the display case had no significant influence on the temperature gradient in the case.

The surface temperature of the objects at their contact surface would naturally depend on the size of the contact surface and on the thermal conductivity of the material. The surface temperature could be several degrees above the surface temperature of the non-covered floor around the object. The measured temperature differences across an object were in the order of 7°C and the relative humidity differences in the order of 17%. Hygroscopic objects should therefore not be placed directly on the floor but should be separated by an insulating material with a thickness of about 0.05 m. or the floor heating should be switched off.

If highly RH-susceptible objects are to be exhibited in the newly designed display cases in the exhibition rooms when the floor heating is on, attention should be paid to insulating the display case interior from the floor. It is then recommended to place insulation material (with a thickness of about 0.05 m) on the heated floor, which can in turn be covered with parquet in order to limit any disturbing visual impact, or the floor heating should be turned off.

Objects in the Stedelijk Museum's collection with a significant surface contact (see Figure 8 for examples) would cause a large insulated surface on the floor with subsequent heating of the lower part of these objects.

The use of underfloor heating would significantly increase the AER of the showcase, with a subsequent increase in the risk of dust deposition on objects. It was estimated that fine dust particles in particular may cause an increase in soiling. This would require a higher cleaning frequency in the display cases, especially during wintertime, unless the case was very well sealed.

Besides the undesirable effect of heating collections, underfloor heating creates an upward air flow, which causes pollutants, such as (fine) dust particles, at floor level to rise and spread in the exhibition room (Raphael and Davis 1999, Schellen 2002). In addition, the risk of water leakage from the heating system in the floor was expected to increase when, for example, objects needed to be fixed to the floor.

To reduce the risk of dust deposits, it was advised that floors in museums with floor heating should be regularly vacuumed and it was also recommended that floor mats be placed at the entrance. Furthermore, it was advised that the undesirable effects of floor heating could best be avoided by adjusting the surface temperature to the lowest temperature possible. At lower temperatures, there would be a smaller temperature gradient and subsequently a smaller RH gradient and a smaller impact on the AER of unsealed display cases.

On a final note, building renovation, the creation of a new exhibition wing and, in this particular case, designing HVAC systems to a museum's specific requirements are long and complex processes. Many parties are involved and communication between all the different specialists can at times prove to be difficult to time efficiently. This can result in the decision-making process not being sufficiently transparent, especially for the user of the building. Interdisciplinary collaboration between the appropriate specialists (architect, engineers) and the museum staff (conservation, collection care departments) is essential from the outset of the project (Neuhaus 2012). The museum staff need to have the opportunity to monitor the design in order to ensure it is adapted to museum needs. The designers are responsible for making the museum aware of the consequences of criteria which have been set down in the program of requirements, but which may lead to undesirable design solutions in the HVAC system. The moment the climate specifications are translated into technical HVAC specifications is indeed one of the most critical in the decision-making process and needs to be given close attention by all parties.

Afterword

At the time of this research, the SMA building was still under renovation and extension. Since then, the collections have been re-installed and the museum has re-opened. Due to the number of "floor" objects which were finally included in the exhibition of the permanent collection, the underfloor heating was switched off. The museum is currently monitoring the RH and temperature in the exhibition spaces in order to evaluate the impact of switching off the under-floor heating on the overall climate within the exhibition spaces in order to decide whether it is necessary to switch it back on.

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