# Displacement ventilation in the museum environment: a case study

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## SUMMARY

The indoor climate in a recently renovated Dutch museum* does not meet design criteria and specifications for preservation although an extensive climate system is installed. Furthermore indoor air quality is poor during high occupancy.
Eindhoven University of Technology (TU/e) performed measurements regarding temperature and relative humidity (Rh) on 20 locations throughout the museum. Also computer modeling was used to research optimizations.
Results show problems partly are caused by malfunctioning of the humidification system. Also the dehumidification system is too low in capacity. Comparing results with the original design parameters based on the strict former guidelines by the Netherlands Institute for Cultural Heritage, indoor climate is only for about 60% of time within limits of the guidelines. These guidelines are comparable to ASHRAE A. Comparing the data with guidelines as given in ASHRAE, which can be considered fair for such a building, more satisfactory results are found. In that case about 80% of time indoor climate conditions in the galleries are within limits.
Literature and measurements show that the used method of ventilating, Variable Air Volume (VAV) combined with displacement ventilation, is not capable to create and maintain stable and homogeneous indoor climate conditions and therefore is an incorrect design choice for a museum. From literature it is known that displacement ventilation causes hygrothermal stratification over the height of the room and therefore over large artifacts. Furthermore VAV is known for its poor humidity control and possible low air quality.
Given the fact that renovating the system technically as well as financially is not an option, it is recommended to optimize the current system. Despite the incorrect design choice, reasonable acceptable climate conditions are achievable this way, without too large hygrothermal stratification.

*the museum is anonimized on request

## INTRODUCTION

Problem statement
For art conservation it is important to maintain more or less strict indoor climate conditions in the museum environment [1, 2]. Measurements carried out by the Netherlands Institute for Cultural Heritage however, showed this was not the case in the presented museum. During the winter of 2005 -2006 very low relative humidities (Rh) were measured in the galleries, as low as 20% Rh. Temperature and Rh also showed large hourly and diurnal fluctuations causing an even higher deterioration risk. Under such conditions it is not acceptable to expose valuable objects.

Purpose of the work
The research has a multipurpose goal. On one hand it is important to find out why specified indoor climate conditions are not met, although a complex climate system is installed. On the other hand there is doubt regarding the suitability of VAV combined with displacement ventilation in the museum environment.

Outline of this article
This article describes the results of the performed literature study and measurements. In a future article results of the simulation study will be described.

## METHODS
The research is divided into three parts:

1. Literature study on 3 different subjects: optimal climate conditions in the museum environment, displacement ventilation and VAV systems
2. Measuring annual indoor climate conditions (temperature and Rh)
3. Simulation study on air flows in the gallery and control of the system

## CASE DESCRIPTION

Description of the building
The museum is housed in a 17$^{th}$ century historic building that is protected by heritage legislation. In 2005 the museum building has been renovated. Purpose of the renovation was upgrading the building so that it fulfills building physically, technically and concerning presentation, to a museum function. Besides an upgrade of the building interior, a climate system with air handling unit (AHU) was installed.
The annual visitor number is around 35.000.

Orientation
The façade of the building is orientated west-southwest. On this side the main entrance of the museum is found and also a number of galleries.
The museum consists of 4 building layers, of which the first is partly below ground level. The façade is symmetrically built. The footprint of the building is about 400 m$^2$ with a total floor area of 1.300 m$^2$. The volume of the museum is about 5.500 m$^3$.
The first building layer, the basement, is accessible at the front side of the building and at the backside through the courtyard. The basement houses some office space, storage, toilets, a kitchen, a wardrobe and the museum café.
On the second building layer the main entrance to the museum is located. Visitors enter the museum by a revolving door. This level contains the admission desk, 4 galleries and museum store.
The third building layer is accessible through the main staircase and an elevator. This level contains 4 galleries of which one is regularly used for activities like receptions or meetings.
The fourth layer or attic contains 2 galleries and the boiler room. The AHU is placed outside on the flat roof of the emergency staircase.

Construction
The bearing facades are constructed out of massive masonry of approx. 0.3 m thickness. During the last renovation they were insulated on the inside with extrude polystryrene (XPS) plating. At the inside of these walls multiplex front plating is placed creating an air cavity.
The floors consist of planking on wooden beams. The base of the pitched roof starts in the attic. The roof is constructed of wooden trusses with an insulated wooden paneling with slate covering on the outside.

Interior
Interior walls are finished with stucco or a wooden front paneling. The paneling is finished with glass fiber wall covering. Against this paneling paintings are hung.
The windows have a wooden window frame. On the inside a second layer of protective glazing is placed. Between the outer and the inner glazing horizontal aluminum slats are used. Wooden shutters are used on the inside of the rooms on the second building level. These shutters are closed outside opening hours. The glass surface covers about 30% of the facade.
Galleries and hall are separated by wooden doors with wired glass. The floors in the galleries on the second and third floor have wooden planking. In the basement, the hall and the second floor, the floors are covered with linoleum flooring or tiles.

Description of the collection
The mixed collection of the museum mainly consists of paintings and objects that tell the history of the city. At the time of investigation a large number of valuable art objects in the museum were on loan. Because of the importance and value of the collection a high quality indoor climate is a must.

Description of the system
The museum has an extensive air conditioning installation with humidification, dehumidification, heating, cooling and air filtering. Additionally from air supply from the AHU, radiators are used in the galleries.
Heat is generated centrally with 2 parallel high efficiency boilers with a total rated power of 122 kW. With these boilers hot water is generated to heat the radiators in the building and the heating sections in the AHU.

Figure 1. The air handling unit is placed on the roof.

To meet the specified climate conditions an air handling unit is used. The specific flow rate of the AHU is about 5.800 $m^3$/h. A schematic representation of the function of the AHU is shown in Figure 2. This is a screenshot from the building management system (BMS).

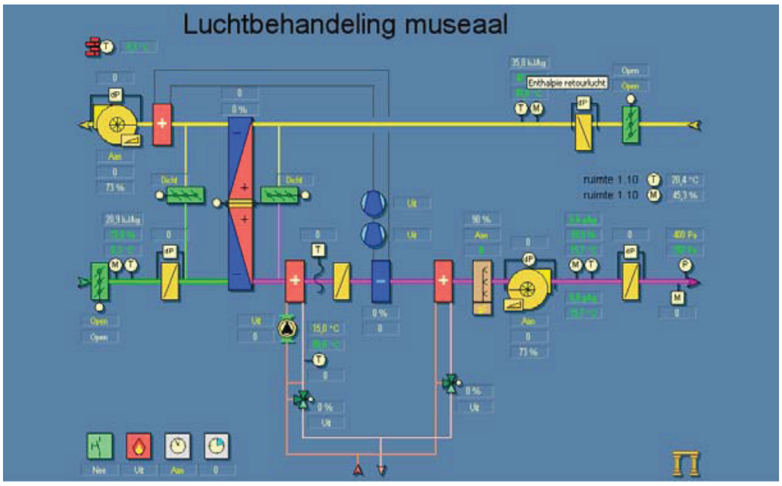

Figure 2. Screenshot from the BMS. A schematic representation of the main components and control of the AHU is shown.

The chiller works on the principle of direct cooling (DX). The air is directly cooled because the evaporator is placed in the supply air stream. The condenser of the chiller is placed in the return air stream.
The AHU is fitted with a steam humidifier. For that reason the unit is connected to a water supply.

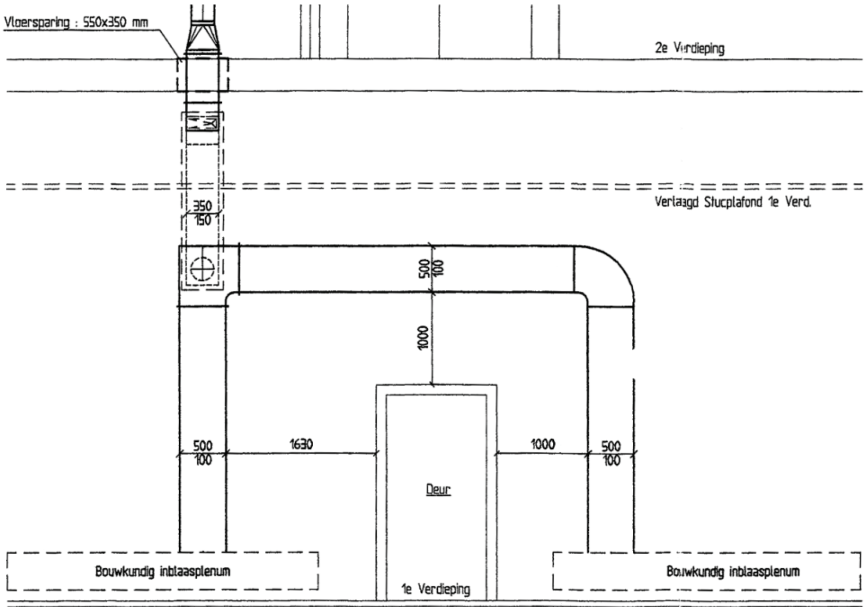

Figure 3. The supply air ducts in the galleries are connected to a wall inlet.

The AHU contains a heat exchanger for heat recovery in winter and summer. It is a so-called regenerating heat recovery wheel with moisture regenerating properties provided by a desiccant coating. Over time the moisture regenerative capacity of the heat recovery wheel however declines.

Ventilation system
According to the specifications the system of air supply in the galleries must be based on displacement ventilation with a variable air volume system (VAV). Due to the lack of proper inlet grills the system is not working as such. For the VAV system a VAV box is mounted in the supply air duct per room.

Control of the system

The climate system is controlled by the BMS. In the BMS individual climate control components as boilers and AHU are linked together. The maintenance company can remotely log into the BMS and thus check the operation of the system and change control settings. The BMS also logs measured data such as temperature, relative humidity and control signals.

Supply water temperature

The supply temperature of the central heating system is based on outside temperature. Therefore an outside temperature sensor on the eastern façade is placed. The control is based on an adjustable heating curve. At a lower outdoor temperature a higher water temperature is created. Radiators are fitted with thermostatic valves.

Air handling unit

The supply air temperature of the AHU is governed by the heating and cooling coils. The desired supply air temperature depends on the measured outside temperature. At higher outside temperatures the supply air temperature will be lower.

The chiller is equipped with two compressors. The second compressor switches only at a higher cooling demand. The intake and exhaust fans in the AHU are regulated by pressure differential. The amount of supply air is per room controlled by a VAV box. The VAV box has a summer and a winter setting. The summer regime is active at an outside temperature of 14 °C or higher. The winter regime is active at outside temperatures below 14 °C. In the galleries temperature and Rh are measured. In summer the valve position of the VAV box is based on measured room temperature and desired air temperature in the gallery (20°C according to the specifications).

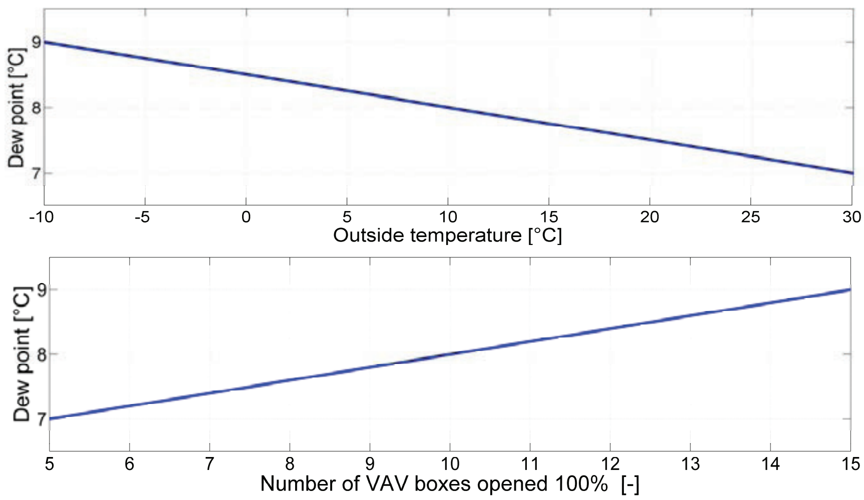


Figure 4. The specific humidity of the supply air is determined by these graphs.

The specific humidity of the supply air is controlled by the steam humidifier and chiller in the AHU. The desired specific humidity of the supply air is determined by two criteria. The BMS calculates a dew point based on the outside air, according to a heating curve-type structure. Also the number of 100% opened VAV boxes is checked by the BMS. Based on the number of 100% opened VAV boxes a second dew point is calculated by a heating curve-type structure (see Figure 4).

For the highest of the two determined dew points the corresponding specific humidity is determined. During winter time the valve position of the VAV box is based on Rh control, dependent on the measured Rh in the gallery. If a Rh lower than the desired value is measured the VAV box will open its valve and supply more conditioned air to the gallery.

The AHU usually functions on 100% outdoor air. Only when the chiller is started air is partly recirculated.

Required indoor climate conditions
For the galleries the indoor climate is specified as follows:

- Minimum temperature in winter depends on building physical limits, setpoint 18°C
- Maximum temperature in summer 25°C, setpoint 22°C
- Allowable temperature fluctuations: 2K per hour and 3K per 24 hours
- Minimum Rh 45%, setpoint 50%, no under running (winter)
- Maximum Rh 55%, setpoint 50%, no excess (summer)
- Allowable Rh fluctuation: 2% per hour and 3% per 24 hours

**LITERATURE STUDY**

Guidelines for indoor climate
In the Netherlands no standards are available that prescribe the requirements for the climate in historic buildings. The owner itself determines what guidelines are used but often lacks sufficient knowledge. Desired limits on temperature and Rh should be determined based of the sensitivity of the collection, building use and building materials.
Apart from climate conditions of the air surfaces conditions are important for preservation of building and interior. Also important is the fluctuation of these values per hour and per day. Based on research several agencies prepared guidelines that describe a relationship between temperature, Rh and collection risk. The main guidelines for the museum environment are prepared by the Dutch Climate Network [1] and ASHRAE [2].

Displacement ventilation
Displacement ventilation is rarely used in Dutch museums. Near the floor, fresh cool air is supplied. Near heat sources the air warms up and rises. Near the ceiling the warmer and contaminated air is extracted. Known disadvantages of displacement ventilation are:

- vertical temperature gradients are created causing local differences in Rh;
- possible cold air flows near the floor;
- heating the room with supply air is not effective: hot air rises up and does not circulate.

The REHVA manual for displacement ventilation [3] shows whenever ventilation should be applied. This is illustrated in Figure 5. In this figure cooling capacity is plotted as a function of air flow, both per m$^2$ floor area.

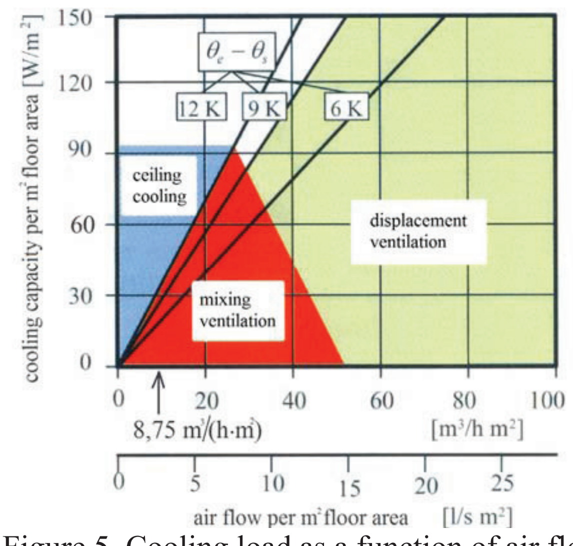


Figure 5. Cooling load as a function of air flow.

According to the design specifications mechanical equipment of the museum was designed at an internal heat load of 9.8 W/m$^2$ and a solar gain factor 0.15. Design criteria specified a supply air flow to the galleries of approximately 8.75 m$^3$/(h·m$^2$). There is only a relatively low air flow necessary because internal heat load caused by people and lighting in this specific museum is low. It follows that a low cooling capacity is expected. According to the graph shown in Figure 5, mixing ventilation is a good choice. With small internal heat loads and low flow rates the guideline shows that displacement ventilation is not a wise choice for the galleries.
In general it can be said that displacement ventilation is not recommended for exhibition spaces with valuable and sensitive art. In these spaces there often is limited heating of the air by lighting, equipment and individuals, as in this case. Guidelines for the indoor climate in museums [1, 2] describe homogeneous and stable air conditions are desired. Displacement ventilation systems are characterized by their thermal and thus hygric stratification. In addition, supply of air at floor level may cause an undesirable flow of dust. For these reasons literature advises not to use displacement ventilation in exhibition spaces [1]. In museums mixing ventilation is recommended.

Variable Air Volume
Known disadvantages of a VAV system are:
- air is supplied with a variable flow;
- Rh control is poor;
- ventilation rate and thus air quality depends on temperature;
- re-heater or radiator heating is often necessary.

In the case that a room is at the desired temperature the supply valve is almost closed. Because of this the amount of ventilation is reduced, possible causing contaminant level to rise. If the supply air also is used to humidify or dehumidify the room, as is the case in the presented museum, no Rh control is possible at all. Characteristics of the VAV system are poor moisture control due to the occurrence of a variable supply flow and inflexibility to meet different climatic parameters. Main advantage of a VAV system is energy reduction.
In the museum environment an air condition of constant temperature and RH is desired. Based on these characteristics VAV systems are considered as inappropriate ventilation systems for exhibition spaces [2]. Using a constant volume system (CAV) is preferred in these situations.
DX cooling
A well known disadvantage of DX cooling is the saw-tooth effect of the supply air temperature [4] caused by the on/off control of the compressors. When using indirect cooling, a more stable temperature and humidity control is possible. Indirect cooling is more expensive however.

## MEASUREMENTS

After analyzing the data conclusions can be drawn regarding the interior climate, functionality of the system and hygrothermal performance of the building envelope. Data of the mechanical system and indoor climate were collected by the BMS and a temporarily installed telemetric monitor system. The BMS controls the climate system, but also stores data of various parameters. This includes supply and return air conditions, air conditions of the galleries and signals sent to the components of the climate system. Air temperature and relative humidity were measured separate by the BMS to assess the indoor climate and check the effect of a displacement ventilation system in the museum environment.

The telemetric measurement system consisted of wireless transmitters which measured temperature and Rh. The data measured by the sensors were sent to the centrally positioned data logger where the data was stored. The connection between data logger and laboratory of the TU/e was performed via cell phone, making it possible to remotely monitor measurements in real time. The temperature gradient was measured in one position in the museum. This measurement was performed using a tripod on which 8 temperature sensors were attached at different levels (see Figure 6).

Figure 6. Test set up for measuring temperature stratification at room level.

Indoor climate conditions

The data obtained by measurement in the galleries are analyzed from July 4th 2007 to November 1st 2008. For all rooms temperature and relative humidity show a day-night variation (see Figure 7). From 10 a.m. to 5 p.m. (opening hours) temperature rises about 2 to 3°C caused by visitors and lighting.

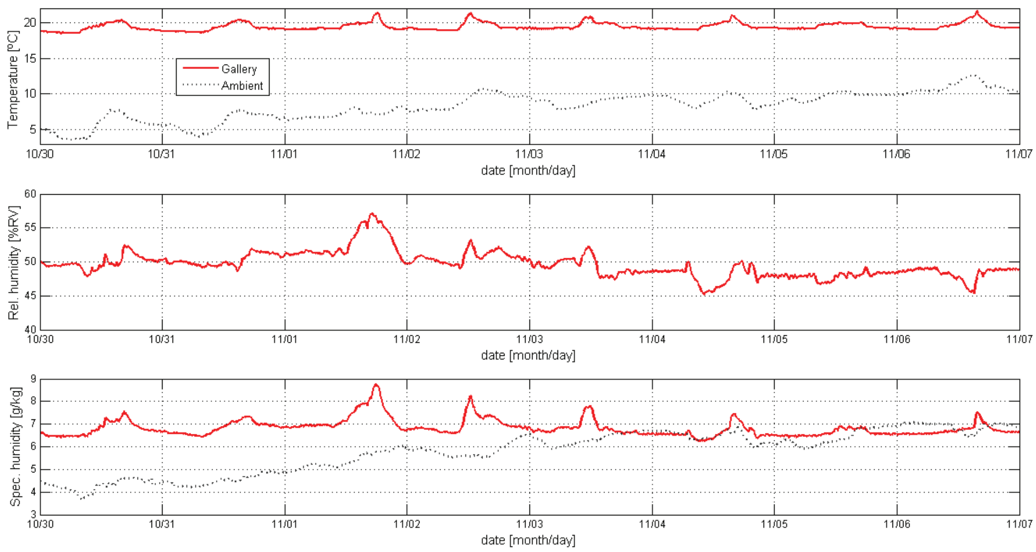


Figure 7. Measured air conditions in a representative gallery from October 30th to November 7th 2008.

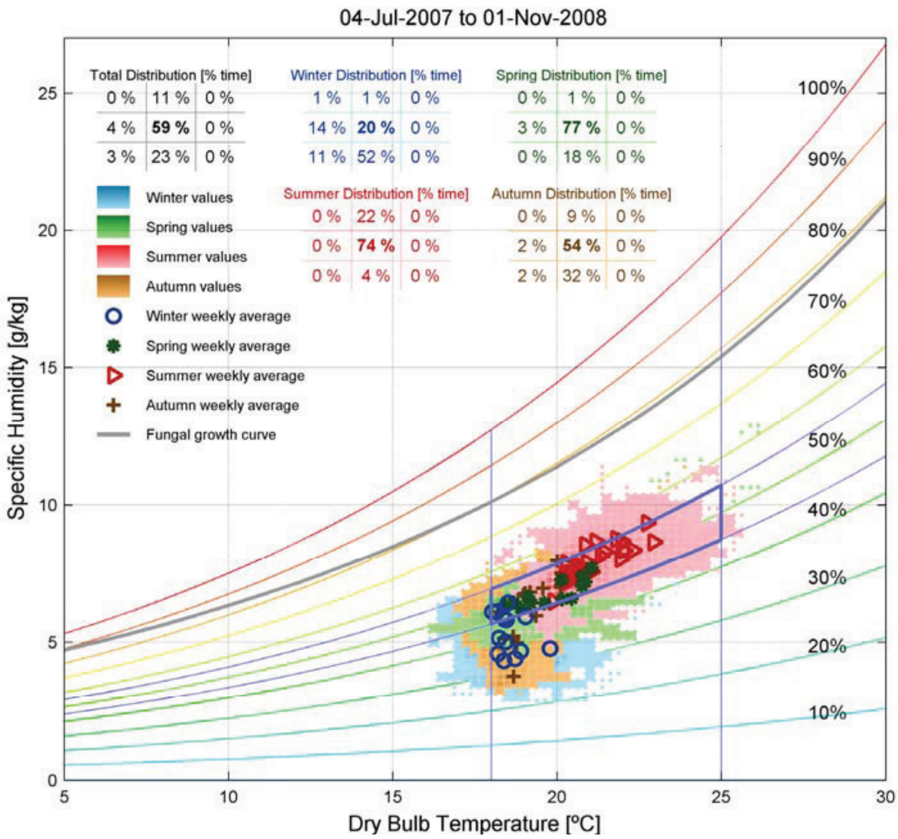


Figure 8. Measured air temperature and Rh in a representative gallery analyzed in the CEC.

In Figure 8 climate conditions measured in an exhibition hall are presented in the Climate Evaluation Chart [5]. For approximately 26% of the time Rh is in the halls below 45%. This is primarily the case during winter time and caused by the failure of the humidifier. Rh variations per 24 hours are very high: for all rooms for more than 90% of all measured data fluctuations are greater than 3% per 24 hours (Figure 9). In none of the galleries temperature exceedance is recorded for more than a few hours (>25°C).

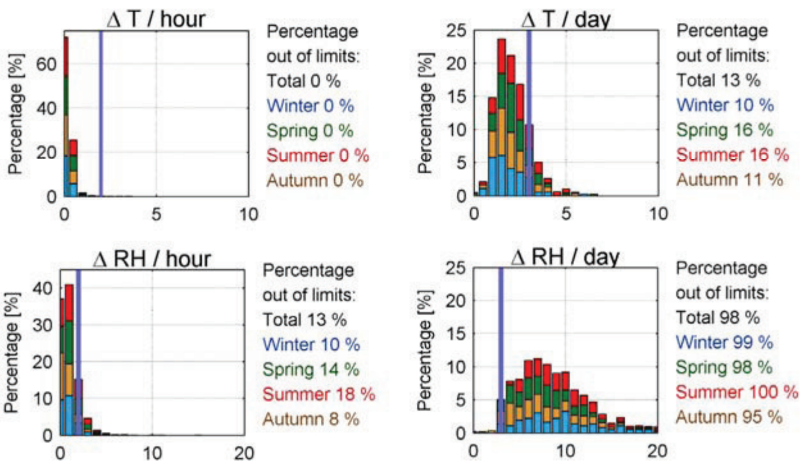


Figure 9. Analysis of indoor climate fluctuations from July 4th 2007 to November 1st 2008.

Stratification

Figure 10 displays results of the stratification measurement on February 12th 2008. In this chart air temperature at different heights is plotted as a function of time. It can be seen that at about 8 a.m. lights are turned on. Air temperature above 3 m increase slightly. Probably around 11 a.m. visitors enter the gallery. In the lover part of the room (a height up to 2 meters) the highest temperature peaks can be seen. Around 5 p.m. temperature increases significantly because people enter for a reading starting at 6 p.m.

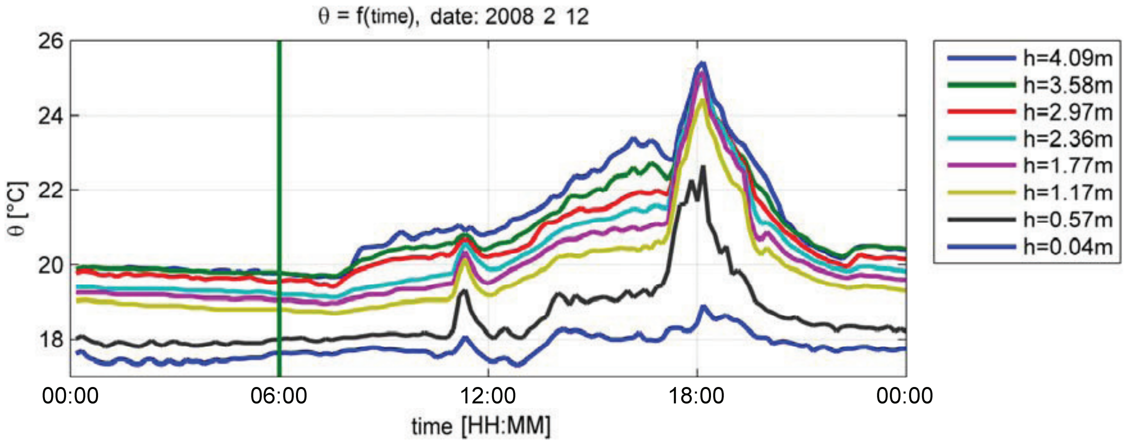

Figure 10. Data from February 12th 2008 showing measured temperature on different heights.

In Figure 11 and Figure 12 temperature difference between different heights and close the floor (h = 0.04 m) is shown: there is a clear temperature gradient visible. Figure 11 shows the measured temperature difference at 6:00 a.m. at different heights and Figure 12 at 6:10 p.m. In these figures temperature difference at a certain height above the floor is indicated in blue. The calculated hourly temperature fluctuations at that time, fluctuations in time, are indicated in green. The black line shows the total temperature change. This is the sum of temperature differences over height and hourly temperature fluctuations. The red continuous line shows the criterion of the temperature change, in this case according to ASHRAE Class A: 4K.

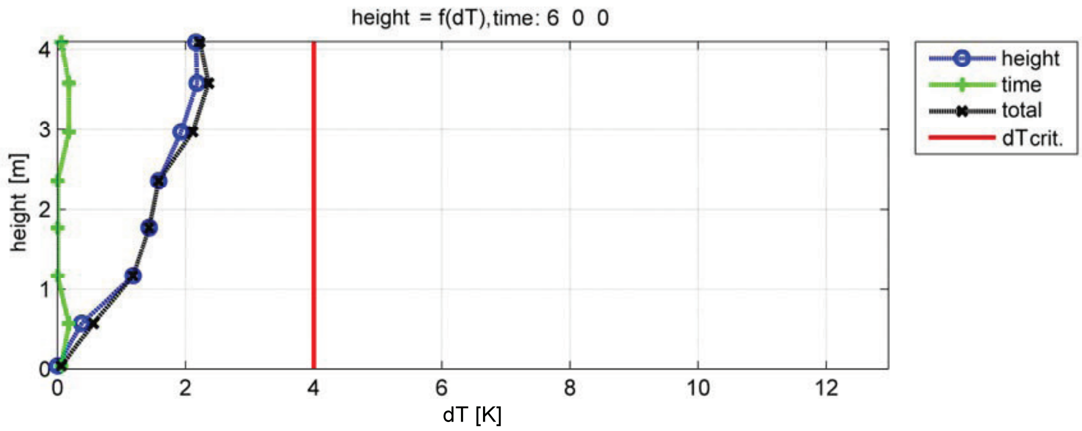

Figure 11. Temperature difference at different heights at 6:00 a.m.

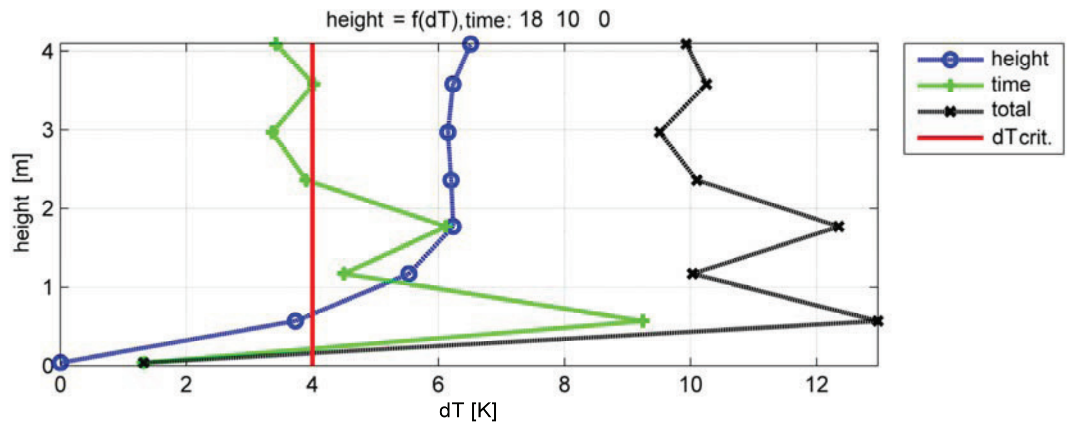

Figure 12. Temperature difference at different heights at 6:10 p.m.

Figure 11 (6:00 a.m.) shows that temperature change (black line) is almost entirely a result of the temperature gradient (blue line). The hourly temperature fluctuations (green line) are practically equal to zero. The total temperature change is equal to 2.3 K. In Figure 12 (6:10 p.m.) is shown that temperature change over the height (blue line) exceeds the criterion of 4K. A high visitor number at this time caused a temperature difference of more than 6K. In addition to this temperature fluctuations are highest (green line) in the lower part of the room (<2 m).

## DISCUSSION

The indoor climate problems in the examined museum are a combination of several factors. First of all the historical building is not suitable for creating a strict indoor climate. The building envelope is not air tight enough and in cold periods condensation or high humidities occur near cold surfaces. Secondly the chosen design is not suitable for maintaining stable and homogeneous museum conditions. Displacement ventilation provides significant hygrothermal stratification over the height of the galleries. Measurements show that displacement ventilation in the galleries leads to undesirable high thermal stratification and thus moisture gradients. Differences in temperature and relative humidity are greater than 4K and 10% Rh over the height of a gallery.

From literature is known that mixing ventilation is better suited for galleries, because temperature and Rh gradients will be smaller due to better mixing of the air volume. Moisture control is not optimal when using a VAV system. The applied VAV system cannot provide the needed ventilation amount due to the control of it. For instance, if there are many people in a gallery for a reception, RH will increase without the system correcting. The current control will close the VAV boxes for this gallery in winter conditions because Rh is judged as sufficiently high.

In the air handling unit a DX cooler is used for cooling and dehumidification. Literature and measurements show that direct cooling leads to poor control of dehumidification and unstable conditions.

The third problem in this case is that, due to an incorrect monitoring system failures were late detected. Failures of the steam humidifier stayed unnoticed during cold periods, resulting in very low Rh in the galleries for long periods.

Although damage directly related to a too large stratification was not found on artifacts, it is recommendable not to place large artifacts near or above air supply grills.

## ACKNOWLEDGEMENT

The authors are grateful to the staff of the museum as well to the client, which has made this research possible.

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