Experimental and Numerical Analysis of a Novel Display Case Design: Case Study of the Renovated Anne Frank House

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ABSTRACT

Many museums are housed in historic buildings, sometimes the building itself is part of the museum collection. Creating a stable environment by providing a nearly constant temperature and relative humidity at correct levels decreases the risk of object degradation. Maintaining this steady indoor environment, however, increases energy consumption and risks to the historic building. Museum display cases offer a solution to the mitigation of risks to which valuable objects may be subjected by providing an extra layer of protection to indoor climate fluctuations. The Anne Frank House is a historic house museum located in Amsterdam. The museum has undergone several renovations in the last years to deal with an increase in the number of visitors to over 1.2 million a year. The original diaries and other documents of Anne Frank are permanently on display in the Anne Frank House. With the recent refurbishment the possibility arose to design a new state-of-the-art display case. This study presents the results of the experimental research related to the design, performed in-situ. The temperature and relative humidity in the new exhibition space and inside the new display cases were monitored to gain insight into the hygrothermal behavior of these controlled environments. A complementary numerical study was performed to investigate effects of dynamic climate control of the exhibition gallery and climate conditions in the display case under various circumstances. Four main conclusions are presented in this paper. The investigated display case design is able to provide a stable relative humidity environment by means of silica gel, while using an active box-in-box climate control system to create stable temperature conditions. The inner case temperature depends on the temperature supplied by the display case air handling unit. Protocols must be in place in case of malfunction or failure of the climate control system of the display case. The air handling unit of the case needs to be shut off to create a passive environment for the objects on display until necessary actions are taken. Exhibition gallery set points can be less stringent when susceptible museum objects are on display in the display case. The environments are separated and provide an opportunity for energy saving set point strategies. The last conclusion drawn is that the numerical study provides valuable insight into imposing dynamic control of set points for temperature and relative humidity in the exhibition gallery and the effect on the display case environment.

INTRODUCTION

Museums are often located in historic buildings. Many historic buildings have been adapted to house museum collections. Often, a heating, ventilation and air conditioning (HVAC) system is installed to provide indoor climate control. This climate control is needed to provide suitable indoor climate conditions for object preservation. Based on limited research in the past and development of precise technical equipment, a constant temperature (T) and relative humidity (RH) were striving for to reduce risks to objects (Brown and Rose 1996). Maintaining this strict indoor climate can result in high energy costs, possible damage to the building itself, and in the case of historic buildings, the desired set points are often not reached (Maekawa et al. 2007; Martens 2012; Ankersmit and Stappers 2016).

The use of museum display cases make it possible to maintain less stringent climate conditions in the exhibition area while providing climate control for objects in the display case. Museum display cases provide an extra layer of protection against (i) physical damage (ii) theft and (iii) inappropriate climate variations (Camuffo, Sturaro, and Valentino 2000). Shiner (2007) described different trends in display case designs throughout the years. In order to buffer T and RH fluctuations, passive systems make use of thermal and hygroscopic inertia. Certain finishing materials or the use of silica gel can create an environment where vapor adsorption capacity is high and RH can be regulated (Romano et al. 2014). Active display case systems rely on equipment to control the internal conditions...
(Michalski 1982; Goli et al. 2017). Although the display case creates a well-controlled microclimate, it provides some risks as well. Air tightness of the display case may trap internally generated pollutants. Examples are organic acids emitted from certain types of wood, reduced sulfur compounds from wool, or even fatty acids from the oil medium found in paintings. Internally generated pollutants from the object itself can build up or be trapped if the display case is well sealed. Ventilating the case requires filters to prevent external pollutants from entering, and increases exchange with external unconditioned air (Ferreira, de Freitas, and Ramos 2015).

This study focuses on the Anne Frank House located in Amsterdam. The museum is housed in buildings surrounding the World War II hiding place of Anne Frank. These buildings are part of the museum collection. Because of its societal value, one of the primary tasks of the Anne Frank House is to preserve the diaries and other writings by Anne Frank. The museum strives to educate and spread awareness on the WWII period in Amsterdam based on Anne Frank’s life story. The collection of the museum is comprised of the building, and interior furnishings. Major collection items are the documents of Anne Frank, including her diaries, which have been listed since 2009 by UNESCO as ‘Memory of the World’. The majority of collection items on display are placed in display cases to provide protection from the impact of high visitor numbers.

Before the renovation, the Anne Frank diary and other documents were exposed to wide daily temperature fluctuations where the room temperature (\(T_{\text{room}}\)) could reach 24°C during opening hours while it cooled down to 19°C during the night (\(\Delta T = 5^\circ\text{C}\)). These fluctuations could be ascribed to the quality of the building envelope, the number of visitors present, and an HVAC system unable to compensate. RH was maintained stable by means of silica gel in the display case. The temperature fluctuations in the display cases were especially of great concern to the museum management for conservation purposes.

Museum management decided that display case renovations were necessary to keep welcoming the high number of visitors to the site without increasing risk to the displayed objects. Since the display cases were not providing the microclimate the museum management desired, a new design was aimed at maintaining the established \(T\) setpoint of 17°C with no permissible fluctuations. Another requirement was to reduce the vibration risks caused by visitors. After careful consideration and discussion with external consultants, a box-in-box principle was adopted for the new display case design. Separating structures into an inner display case and an outer display case provided less risks to the diary in terms of vibration. The air cavity that was created by this box-in-box principle lent itself to \(T\) control. The cavity separating the inner display case from the outer one, can be cooled to provide stable internal \(T\) conditions. Silica gel in the inner airtight case provides a stable RH. The objects, such as the diary, are placed in this inner compartment. In-depth details and description are provided in the Section ‘Display cases’.

Though a plethora of research can be found on both active (Michalski 1982; Goli et al. 2017) and passive (Schieweck and Salthammer 2011; Perino, Filippi, and Bonvicini 2012; Romano et al. 2014; Ferreira, de Freitas, and Ramos 2015; Samadelli et al. 2018) display cases, an active box-in-box principle used for a display case is novel. In the current study, active \(T\) control has led the box-in-box design while RH is controlled passively. This in contrast to most literature where RH control is primary in the design and evaluation of collection care. However, varying \(T\) can lead to RH fluctuations in a display case and this influence should not be underestimated (Romano et al. 2014). Stabilizing \(T\) results not only in a more stable RH, it also reduces the risk of chemical degradation of paper objects.

The goal of this study was to obtain insight into the following objectives:

- Evaluate the performance of the novel display case design using experiments and modeling simulations,
- Evaluate display case design with active \(T\) control as a measure of preventive conservation for paper objects,
- Gain insight into the relation between the established exhibition room and display case inlet conditions on the \(T\) and RH distribution of the display case,
- Gain insight into performance behavior by evaluation of predicted performance for one year of exhibition room conditions.

**Experimental setup**

To structure the research the following methods were used during this study. First, a description of the museum, the novel display case design and all systems involved in climate control is given. Second, the measurement setup and experiments performed are described in detail. Lastly, the numerical model is explained that was used for predictive performance simulations.

**Site description**

Figure 1 illustrates the museum exterior and interior. The museum is located in the city center of Amsterdam in two seventeenth century canal houses. The museum
has undergone several renovations to deal with the increase in the number of visitors to over 1 million a year. Over the years, additional buildings were annexed to use for museum facilities such as entrance, cafe, and offices. The galleries can be divided categorised as those the main house, the secret annex, the diary gallery and the general exhibitions. The general exhibitions are housed in a refurbished addition. The canal houses have an original brick masonry exterior wall, internal separation walls finished with drywall sheets, and wooden floors covered with linoleum. Adaptations to the building have been made to fit a hybrid climate control system. Conditioned air is supplied by air handling units (AHUs) and in certain galleries only radiators are present for heating purposes. The AHUs are located on the roof of the buildings. Once the air is conditioned through either heating, cooling, dehumidification, humidification, and filtering it is supplied to the galleries. Certain galleries make use of an extra heater in the supply duct to reheat the air just before being delivered to the gallery. The galleries are all in open connection with each other. This means the air is distributed based on pressure, concentration, and temperature differences.

**Gallery**

An important gallery in the museum is the exhibition gallery where manuscripts written by Anne Frank are on display. The exhibition gallery is rectangular in shape, 13.1 m deep and 4.8 m wide. Windows are located on the northwest wall facing the canal (see Figure 2). Visitors enter through a hallway and descend a three-step staircase into the exhibition gallery. A red-colored wall is located in the center of the room as a backdrop for the display case containing one of the diaries of Anne Frank (DC1). Behind the red wall, near the exterior façade, two other display cases show other writings by Anne Frank (DC2 and DC3). The exhibition gallery climate is controlled by one Air Handling Unit (AHU_{room}). The supply and return grilles for the AHU_{room} are located at the canal side of the building and additional supply grilles are placed in the three-step staircase and near the entrance area of the gallery. These extra supply grilles create enough mixing ventilation for a homogeneous indoor climate.

Figure 3 shows the HVAC system placed in the technical area below the exhibition gallery. The upper elevation shows the AHU_{room}, while the lower elevation shows the AHU assigned to the display cases (AHU_{case}). AHU_{room} preconditions the air by means of humidity control and temperature control. The return duct of the exhibition gallery is connected to AHU_{room} for recirculation purposes. By means of a bifurcation the return duct of AHU_{room} is also connected to AHU_{case}. AHU_{case} conditions only for air temperature.
Figure 2. Floorplan of exhibition gallery with T/RH sensor locations and positions of the air in- and outlets with the air volumes involved.

Figure 3. Sections of AHU_{room} and AHU_{case}. Image adapted from Breman.
The use of display cases makes it possible to relax previously adopted strict room set points of 50 ± 5%RH and 20 ± 1°C. Museum management adopted the idea for less stringent RH set points. RH is allowed to fluctuate within lower and upper limits of 45–60%. The exhibition gallery T set point was kept at 20 ± 1°C.

Display cases
With the refurbishment it became possible to improve the display case design. Past measurements showed that the display cases could stabilize RH, however, T fluctuated according to gallery conditions. The newly developed display cases had the objective of stabilizing both T and RH throughout the year, reducing risks caused by vibrations, increasing safety, decreasing possible risks by internal and external pollutants, and decreasing risks caused by illumination. It took a number of years to develop the concept and finalize the design by the Anne Frank House, Getty Conservation Institute, multiple companies, the Cultural Heritage Agency of the Netherlands, and the Eindhoven University of Technology.

The result was a state-of-the-art display case design consisting of a larger outer display case and an inner display case (i.e. a box-in-box design). Figure 4 provides a schematic view of the cross section of the display case. The larger case was used to create space for air ducts that supply preconditioned air into the air cavity that separates the outer from the inner display case. The outer display case was placed on the new raised floor which leads directly to the technical area below. The inner case was attached to steel beams fixed directly to the walls of the outer case. Injected air overflowed partly into the technical room and partly to the exhibition gallery by exfiltration. The inner display case air temperature (T_{a,case}) has a set point of 17.5°C without permissible fluctuations.

The inner display case was separated into two compartments. The lower compartment houses two drawers for preconditioned silica gel for RH management. The upper compartment displays the museum objects. A gap of 17 mm between the object compartment and silica gel compartment provides sufficient moisture exchange to create a stable environment. By means of diffusion principles RH should stabilize in both compartments at 45%RH. The result should be a constant RH of 45% in the inner display case due to the preconditioned silica gel. The inner case was sealed to limit air exchange between the cavity area and object area. Air exchange rates (AERs) were calculated from experimental testing by the manufacturer after constructing the cases (AER DC1 = 0.1335/d; AER DC2 = 0.0943/d; AER DC3 = 0.0802/d). These AER experiments were performed based on the work of Thickett, David, and Luxford (2005). The display case was constructed with steel, glass and finished with the nonporous, surfacing material Corian (acrylic resin mixed with natural minerals). Figure 5 shows impressions of the display case design while opened.

Experimental campaign
During the experimental campaign the indoor climate of the exhibition gallery and the environment within the display cases were monitored. This campaign was used to gain insight into the box-in-box concept and the influence of the room conditions on the inner display case. A preliminary experimental campaign

![Figure 4. Simplified cross section of display case with locations of combined T/RH sensors and surface T sensors.](image-url)
was carried out at the manufacturer’s premises as soon as one of the cases was finalized. This preliminary campaign was used to pinpoint the airstream behavior in the cavity. Several inlet air velocities were investigated and temperature fluctuations were imposed by means of an external heat source. This provided initial insight into the potential of this novel display case design.

The measurement campaign held at the refurbished exhibition gallery ran from May 7th until June 29th 2018. This provided limited time for experiments from the installation of the display cases in the gallery to the actual opening to the public.

**Measurement setup**

Figure 2 illustrates the floor plan of the exhibition area. Two T/RH sensors were mounted near the wall at a height of 1.50 m. These were placed near the Building Managements System (BMS) sensors that monitored the indoor environment of the area. A third sensor was placed on top of the red wall at a height of 2.20 m to measure possible vertical stratification. Another sensor monitored the inlet T/RH of the exhibition gallery near the Prinsengracht (canal) wall façade.

Figure 4 shows the locations of the combined T/RH sensors and the surface temperature sensors ($T_s$). The remaining display cases were equipped with the same number of sensors and at similar locations inside the cases. Two T/RH sensors were used. One to measure $T$ and RH of the inner display case near the objects on display ($T_{a,case}/RH_{a,case}$) and one to measure the outlet conditions ($T_{a,outlet}/RH_{a,outlet}$). Two surface negative temperature coefficient sensors (NTC) were additionally attached per transmitter to measure $T_s$. The surface temperature at the inside of the inner display case was measured at the center ($T_{s,center}$) and near the edge ($T_{s,plenum}$) of the glass plate. This was done to locate non-uniformity in $T_s$ caused by the $T_{a,inlet}$. The two NTCS in the outer display case were used to measure inlet $T_s$. One is located in the lower plenum ($T_{a,inlet,lower}$) and one in the right side plenum ($T_{a,inlet,right}$).

The sampling interval was 1 min. A small interval was chosen to be able to observe sudden changes in the $T_{a,inlet}$. Eltek measuring equipment was used with combined $T$ and RH Sensirion sensors providing a measurement accuracy of ±0.4°C and ±3%RH provided by the manufacturer (Eltek). An Eltek RX250AL data logger was used to collect, store and send data to a server at Eindhoven University of Technology.

Before the measurements took place, the measurement equipment (specifically the T/RH sensors) were calibrated. This was done by comparing the Eltek sensors to a reference sensor of which the uncertainty is known. After calibration the overall accuracy of the sensors was better than the accuracy provided by the manufacturer. A precise calibration was necessary since the museum required that no fluctuations should occur near the objects in the new display case design.

**Experiments**

Nine experiments were performed to investigate the influence of $T_{room}$ on the $T_{a,case}$. The experiments were mainly focused on the behavior of $T$. RH around the object was controlled by silica gel in the inner display case. In the first 7 experiments no silica gel was present and the inner display case had no RH control to eliminate influence on RH stabilization by $T$ control of the case.

Table 1 provides an overview of all the experiments conducted. The first experiment set strict boundary conditions for $T_{room}$ and $T_{a,inlet}$ for approximately 5 days. $T_{a,case}$ could vary and provided insight in the response time of the cases. Experiment 2 was performed over 8 days to analyze what would occur in an extreme situation where the AHU case might malfunction for a longer period. Experiment 3 was executed to test the control setting that could be used in emergencies. This was a requested setting to enable last-minute turning of the pages of Anne Frank’s documents before visitors would arrive if necessary. After manually selecting this setting, $T_{room}$ would cool back from 20 to 18°C within one hour. In experiment 4 the display case could be opened to take out the object or turn the pages. The opening of the case would normally take less than a few minutes, but for the
In experiment 5 the effect of high gallery temperatures was examined over the course of five days. Experiment 6 used the standard control setting for a period of seven days. $T_{\text{room}}$ was set to 20°C and the $T_{a,\text{case}}$ setpoint was leading for a fluctuating $T_{a,\text{inlet}}$ to keep a constant 18°C in the inner display case. This setting was the regular operational mode of AHU$_{\text{case}}$ and was not described in the results section. Results of experiment 6 can be found in the appendix. Experiment 7 was used when museum staff wanted to turn a page. $T_{\text{room}}$ would cool during the night to match $T_{a,\text{case}}$ in avoidance of a temperature shock when the display case was opened. This setting was for planned work related to the display cases. The final experiments were in preparation of the opening of the exhibition gallery to the public. The silica gel was added to the inner display compartment and RH$_{a,\text{case}}$ was monitored (experiment 8). The last experiment had boundary conditions for $T_{\text{room}}$ and $T_{a,\text{case}}$ being in operational use and allowed visitors to be present in the exhibition gallery.

### Numerical model

A coupled multiphysics model was built with the COMSOL software to perform simulations in a complex 2D and 3D geometry (COMSOL AB).

#### Model domain and grid

The model was set up in both 2D and 3D. The 2D model was built using the geometry of display case 1 to establish whether the multiphysics settings were computable for this type of model set-up (Figure 6). Symmetry is applied to decrease computational time while simulating. $T_{s,\text{center}}$, $T_{s,\text{plenum}}$, and $T_{\text{outlet}}$ are used as locations to compare experimental data with the simulated data. These locations are used to validate and compare the model over a timeframe whereas $H_{\text{line}}$ and $V_{\text{line}}$ are used to compare different model behavior in certain areas of the geometry.

After establishing that the 2D model converged, a 3D model was developed (Figure 7). This model better resembled reality. Certain simplifications were
made to the geometry to reduce computational time. Inlet and outlet edges and planes were kept similar to the display case design.

In order to check whether results are influenced by the grid size, a grid sensitivity study was performed. Figure 8 shows the coarse, medium and fine grids that were made with the COMSOL physics controlled grid builder. The number of cells is 5791, 8837, and 46,738 respectively. Computational time and effort increases when the number of cells increase, however, accuracy might increase as well.

**Boundary conditions and solver settings**

The model built in the current study used the physics modules for heat transfer and turbulent flow. Radiative heat transfer between wall surfaces was included with the surface-to-surface radiation module and conductive heat transfer was modeled with the non-isothermal flow multiphysics coupling. The model combined conductive heat transfer through the display case envelope, convective heat transfer through the supplied air, and radiant heat transfer. The model was able to perform transient simulations. Figure 7 (center) shows the inlet and outflow planes of the 3D model. Figure 7 (right) shows the diffuse surfaces included for radiative heat transfer. The material properties were taken from the manufacturer where possible. Due to some simplification in the geometry, not all structure elements were modeled.

The inlet boundary conditions were set based on the measurements for validation. $T_{\text{inlet}}$ for the validation simulation was based on the dynamic experimental measurements performed in this study. A heat flux was imposed to represent $T_{\text{room}}$.

Air velocity was set to a uniform 1.5 m/s for all the three inlets. The turbulent flow module used turbulence model $k-\varepsilon$. Different adaptations of this model are more widely used in indoor airflow studies (Chen 1995). Turbulence model $k-\omega$ was used to see if this turbulence model gains better agreement with the experimental data obtained from the experimental campaign (Wilcox 1998).

**Results**

**Experimental results**

In the following paragraphs, the results of the experiments described in Table 1 are provided. The results are described for display case 1 since they are similar for all display cases and were performed simultaneously.

**Outdoor conditions**

Figure 9 provides results of outdoor measurements collected by the Royal Dutch Meteorology Institute. These measurements were done at Schiphol Airport, located 12 km from the Anne Frank House. During several weeks the $T_{\text{outdoor}}$ was above 25°C. $R_{\text{H, outdoor}}$ was between 40 and 95%. Specific humidity went from 5 g/kg during early May to peaks of 15 g/kg at the end of May, early June. During this period the Diary Room investigated in this study was able to condition $T$ and $RH$ towards the wanted set points.

Figure 10 shows comparison between Eltek data with those provided by the BMS system for the three display cases studied. The BMS sensors direct the air handling unit that conditions all display cases. Overall, DC1 showed very limited variations between the BMS and Eltek measurements. $\Delta T$ showed two peaks of $-0.1°C$ and $-0.2°C$. Display cases 2 and 3 had limited $\Delta T$ variations, $-0.1°C$ and $-0.15°C$, respectively. Both the BMS and Eltek sensors were calibrated and showed no variations.
Figure 8. Coarse (left), medium (center), and fine (right) grid used for grid sensitivity analysis for the 2D and 3D cases.

Figure 9. Outdoor temperature, relative humidity, specific humidity and irradiance of the Amsterdam location (Schiphol) during the measurement period. Starting dates of experiments are expressed by the vertical lines.
Regular and malfunction experiments

For sake of conciseness the results discussed are measurements from DC1. This display case displayed the red checkered diary of Anne Frank. Figure 11 shows the results of the first two experiments for the display case design. The first experiment started at May 16th at 08:00 h. The dark gray line represents the room conditions. The magenta line shows the air conditions in the inner display case. The orange line shows the conditions of the return air in the outer display case and the green line provides information on the inlet conditions of the display case. Peak A and drop B are discussed in the description of Figure 11. Under stable boundary conditions of \( T_{\text{room}} \) and \( T_{\text{inlet}} \), the inner display conditions were stable as well. Under fluctuating \( R_{\text{room}} \) and \( R_{\text{outlet}} \), the \( R_{\text{a, case}} \) in the inner display case remained stable even though it was an empty case and no RH regulation was present.

The second experiment in which the AHU of the display cases was turned off, started at 9:30 h on May 21st. This graph shows that as soon as the \( T_{\text{inlet}} \) alters, \( T_{\text{a, case}} \) responds almost immediately. The response time of the system in this test was 34 h and 45 min, given that the step change of \( T_{\text{a, case}} \) was from 17.2 to 19.8°C. \( R_{\text{a, case}} \) remained stable during this experiment.

Opening of case with control setting 1 and extreme \( T_{\text{room}} \) experiments

Figure 12 illustrates the results of three experiments. In experiment 3 \( T_{\text{room}} \) was set to drop from 20 to 18°C within an hour. This is shown in the drop of the gray line and the sudden rise in \( R_{\text{a, case}} \) (magenta line). As soon as the emergency setting was operated \( T_{\text{room}} \) dropped, however, \( \text{AHU}_{\text{room}} \) was not able to dehumidify the cold air before being supplied to the exhibition gallery. This resulted in a high \( R_{\text{room}} \) nearing 70% RH.

In experiment 4 the display case was opened (May 29th at 11:30 h) and closed after one hour. An increase of \( R_{\text{a, case}} \) and \( x_{\text{a, case}} \) can be seen (magenta line). Due to the opening of the case \( R_{\text{a, case}} \) increased to \( R_{\text{room}} \) conditions which turned out to be high since the system was not able to dehumidify the air before it entered the exhibition gallery. After closing the display case the sealed case created a stable \( R_{\text{a, case}} \), however, at an inappropriate RH for preservation needs.

In experiment 5, the \( T_{\text{room}} \) setpoint was increased to 24°C. This experiment started on May 29th at 12:30 h. Figure 12 shows the increase in \( T_{\text{room}} \) which lasted several days. Four hours after increasing \( T_{\text{room}} \) a peak was visible in \( T_{\text{a, case}} \) (purple arrow Figure 12), caused by a sudden rise of the supply air temperature. The peak of \( T_{\text{room}} \) started at 18:00 h.
and $T_{\text{inlet}}$ rose from 17 to 20.5°C, the display case $T_{\text{a,case}}$ peak started with a delay at 19:00 h and rose to 19°C in an hour. At the moment, the authors cannot fully explain why the peak occurred during this experiment. $RH_{\text{a,case}}$ and $x_{\text{a,case}}$ were less affected by the change in room conditions. $RH_{\text{outlet}}$ (orange line) showed high relative humidity while $RH_{\text{room}}$ decreased significantly from 70% to 50% RH. The high value for $RH_{\text{outlet}}$ might result in increased condensation risk on the cold surfaces of the display case. However, air velocity at the outlet location was high which resulted in limited stagnant air present (Scott 1994).

Opening of case with control setting 2 and RH control experiments

Figure 13 shows the results for experiments 7, 8, and 9. Before these experiments took place the figure shows a rise in $T_{\text{a,case}}$ conditions starting from 09:00 h. During the morning, light fixtures were installed at the ceiling of the gallery and the display cases were frequently opened to position a mockup of the diary to adjust the light beams.

In experiment 7 $T_{\text{room}}$ was cooled to 18°C overnight. This experiment started at 15:00 h on June 11th. Figure 13 shows that the exhibition gallery reached the set point of 18°C at approximately 18:30 h. Considering that the display cases would be opened the next day between 08:00 and 09:00 h.

At 16:00 h on June 11th silica gel was added (experiment 8) to the inner display case to create a stable 45% RH environment. The figure shows that in a gradual manner $RH_{\text{a,case}}$ decreases towards 55%.

The next day at 08:00 h the case was opened and the museum items were placed in their new display. $T_{\text{room}}$ was set to operational mode, 20°C. After placement of the objects a spike in $RH_{\text{a,case}}$ can be found which indicated opening the display case. The silica gel managed to lower $RH_{\text{a,case}}$ towards 48%. Figure 14 shows the climate in and around the display case during experiment 9.

Figure 14 shows experiment 9. Every system was set to operational mode for both $AHU_{\text{room}}$ and $AHU_{\text{case}}$. Visitors were able to enter the exhibition gallery and view the manuscripts of Anne Frank on display. The figure shows $T_{\text{room}}$, to constantly fluctuate around a set point of 20°C with $\Delta T$ of 1.8°C. The inlet conditions of the display case showed a steady profile resulting in a stable $T_{\text{a,case}}$ (17.4 ± 0.5°C).

$RH_{\text{a,case}}$ around the manuscripts was very stable. Though $RH_{\text{room}}$ was kept between the set points of 45–60%, $RH_{\text{outlet}}$ shows values up to 80%RH, mainly
due to the low $T_{\text{inlet}}$ and not being able to control RH in AHU$_{\text{case}}$. The small dips during the week of June 15th were caused by tweaking the control settings of AHU$_{\text{case}}$. The dip around June 28th in $T_{\text{inlet}}, T_{a,\text{case}},$ and $T_{\text{outlet}}$ was caused by a change in control setting bringing the $T_{\text{set point}}$ of the display case down to 17°C upon museum management request. In the days preceding June 21st, RH$_{\text{room}}$ exceeded the upper limit of 60%. With some slight adaptations to the cooling system RH$_{\text{room}}$ remained within the set point limits during the following days.

RH$_{\text{outlet}}$ remained high due to the low $T_{\text{inlet}}$ and the fact that this air stream has no RH control in AHU$_{\text{case}}$. Part of the outlet air entered the exhibition by means of infiltration. The remainder overflowed to the technical room below the exhibition gallery. This might have caused some locally deviating RH$_{\text{room}}$ levels. Since the objects were located in buffered airtight display cases these deviating RH$_{\text{room}}$ levels were not a preservation risk for these objects.

**Modeling results**

Figure 15 shows the results for the 2D grid sensitivity analysis performed for the $k$-$\varepsilon$ turbulence model. This model is commonly used in CFD and uses a two-equation mathematical model to provide a general description of turbulence flow. The coarse and medium grid show similar results for three locations. The measurement locations can be found in Figure 6. The boundary condition in the numerical model for $T_{\text{inlet}}$ (gray line) was taken during experiment 5. $T_{\text{room}}$ at that moment was constant at 24°C and $T_{\text{inlet}}$ showed a peak of 4 K that resulted in a peak in $T_{a,\text{case}}$ as well (see Figure 12).

For the grid sensitivity analysis the coarse and medium grid were almost overlapping indicating grid independency. The fine grid shows no significant improvement compared to the medium and coarse grid. The coarse grid was sufficient to predict surface temperatures of the inner display case influenced by the imposed room conditions without a significant increase in computational time.

Figure 16 shows the grid sensitivity analysis over a horizontal line and a vertical line in the 2D case. The $k$-$\omega$ turbulence model was added to investigate if it would perform more accurate near the wall-region. No significant deviations are shown and the coarse grid in combination with the $k$-$\varepsilon$ turbulence model seemed sufficient for the remainder of simulations.
Validation

Figure 17 shows the comparison between simulation outcomes and experimental data during experiment 5 for different turbulence models and both 2D and 3D case. Exact compared measurement locations can be found in Figures 12 and 13. The results show that the amplitude of the peak imposed by $T_{\text{inlet}}$ were buffered partially and delayed in time. Looking at the agreement between measurements and simulations, the 3D case underestimated the $T_{\text{center}}$ peak (Figure 17 left). There might be a 3D flow component which caused this deviation compared with the 2D case results. The results near the inlet plenum shown in the middle figure of Figure 17, show that for the 3D case both turbulence models underestimated $T_s$. The 2D case shows good agreement with the measurement results. For the outlet location the simulation results follow the $T_{\text{inlet}}$ line and buffer some oscillation (Figure 17 right).

Comparing different turbulence models only shows significant deviations for the $T_{\text{outlet}}$ data for $k-\omega$ turbulence model where it agrees slightly better than the $k-\varepsilon$ turbulence model.

To quantify whether the computational model was representing reality and to check which turbulence model performed more accurately, the measurement data and simulated outcome were compared by means of validation metrics. The fractional bias (FB) can be used to quantitatively compare simulated output with measured data with the note that parameters with both negative and positive values were not suitable for this metric (Roache 1994; Schatzmann, Olesen, and Franke 2010).

$$FB = \frac{\bar{O} - \bar{P}}{0.5 \cdot (\bar{O} + \bar{P})}$$

(1)

Where $O$ are the measured (observed) data points and $P$ are simulated (predicted) data points. The overbar shows that the average over all data points needed to be taken as input in the equation.

Another method for model comparison between model and experimental results was the fraction of data within a factor. The factor 1.05 is commonly used for temperature comparisons (Schatzmann, Olesen, and Franke 2010).

$$\text{FAC } 1.05 = \frac{1}{N} \sum_{i=1}^{N} n_i$$

(2)

where:

$$n_i \begin{cases} 1 & \text{for } 0.95 \leq \frac{P_i}{O_i} \leq 1.05 \\ 0 & \text{otherwise} \end{cases}$$
Where \( N \) is the number of data points, \( P_i \) are the predicted values and \( O_i \) are the observed values.

Two other validation metrics that were often used in building simulation were the mean bias error (MBE) and coefficient of variation root mean square error (CV RMSE). These indices were used for model accuracy of the simulation model compared to measurement data (Coakley, Raftery, and Keane 2014).

\[
\text{MBE}(\%) = \frac{\sum_{i=1}^{N_p} (O_i - P_i)}{\sum_{i=1}^{N_p} O_i} \tag{3}
\]

\[
\text{CV RMSE}(\%) = \sqrt{\frac{\sum_{i=1}^{N_p} (O_i - P_i)^2 / N_p}{O}} \tag{4}
\]

Table 2 shows the results for all validation metrics. The FB metric shows good agreement with the 2D model in all locations. The center location of the 3D \( \kappa-\varepsilon \) comparison shows exceedance of the range for the fractional bias. FAC 1.05 was still in agreement for both the 2D and 3D cases. In general, a good agreement was shown for the reviewed measurement locations. The 3D \( \kappa-\varepsilon \) case under predicted the peak in the center of the display case (0.620). This can be ascribed to the two flows coming together in the center of the air cavity creating an area with overpressure where lower velocities were present. The current 3D \( \kappa-\varepsilon \) model under predicted temperature at this location while still being in compliance with the majority of validation metrics. The MBE and CV RMSE both showed disagreement for the 2D fine grid case with the \( \kappa-\varepsilon \) turbulence model. The CV RMSE also showed disagreement for the 3D case for both \( \kappa-\varepsilon \) and \( \kappa-\omega \) turbulence models for \( T_{\text{center}} \).

**Results simulations**

After model validation, a study was performed to see the effect of imposed room boundary conditions on \( T_{\text{case}} \). Museum management already approved regulating RH within an upper and lower limit, performing a simulation in which \( T_{\text{room}} \) was able to fluctuate within a controlled upper and lower limit provided insight into the performance of the museum display case. Since collection environmental requirements were addressed by the museum display case, the \( T \) and RH set points for the exhibition gallery were determined by visitor thermal comfort. The elaborate study of Kramer et al. (2017a) used a dynamic control algorithm to dynamically determine the set points for \( T_{\text{room}} \) and \( R_{\text{room}} \). The collection requirements were based upon the ASHRAE climate classes (ASHRAE 2015). The visitor thermal comfort requirements were based

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*Figure 14.* Indoor climate conditions of the exhibition gallery (gray) and display case (colored) during experiment 9. The exhibition gallery was opened to public during this experiment and silica gel controls RH\(_{\text{case}}\).
Figure 15. Grid sensitivity analysis for 2D model for $T_{s,\text{center}}$ (left), $T_{s,\text{plenum}}$ (center) and $T_{\text{outlet}}$ (right). Measurement locations can be found in Figure 6 where $T_{s,\text{center}}$, $T_{s,\text{plenum}}$, and $T_{\text{outlet}}$ are pictured.

Figure 16. Grid sensitivity analysis through horizontal (left) and vertical (right) plane for 2D model. Locations of the lines can be found in Figure 6.

Figure 17. Comparison between experimental results and simulation results for $T_{s,\text{center}}$ (left), $T_{s,\text{plenum}}$ (center) and $T_{\text{outlet}}$ (right) in the 2D and 3D case for several turbulence models.
upon adaptive temperature limits for museums (Kramer et al. 2017b).

In the current study the dynamic control algorithm was used to calculate the upper and lower limit for T and RH while complying with ASHRAE climate class AA. Class AA is the most strict climate class with proofed short-term and seasonal fluctuations to decrease mechanical risk to fragile and susceptible objects.

Figure 18 shows the results for imposing a simulated indoor temperature as $T_{\text{room}}$ (light gray). This indoor temperature was based on the study of Kramer et al. (2017a). The dark gray line provides the 30 d moving average to see the seasonal fluctuations. The colored dash-dotted lines show the results of an actively controlled case temperature. $T_{s,\text{center}}$ (orange) and $T_{s,\text{plenum}}$ (blue) show a stable line throughout the year indicating AHU$_{\text{case}}$ being able to maintain a set point of 17°C. Another simulation has been performed where AHU$_{\text{case}}$ was turned down and the display case could be seen as a passive system. The results for this simulation in Figure 18 show an increase in surface temperature of the case for the passive case compared to the fully active $T$ controlled system. Besides a seasonal fluctuation, shorter fluctuations are also present and not thermally buffered by the system.

The results of this study show that though $T_{\text{room}}$ varies throughout the year, $T_{\text{case}}$ is able to be conditioned in a stable manner in the active situation with imposed boundaries for $T_{\text{room}}$. $T_{\text{case}}$ is complying with the museum requirements of 17.5°C without fluctuations.

**Discussion and conclusions**

The display case was developed and designed to create a stable environment around culturally important manuscripts. The use of silica gel in the inner airtight display case and flushing the air gap between the outer and inner vase with conditioned air proves to be effective.

In case of malfunctioning of the climate control system or AHU components, $T_{\text{inlet}}$ will follow imposed $T_{\text{inlet}}$ conditions. Protocols need to be in place for museum staff to reduce risk impact when $T_{\text{inlet}}$ Conditions are not appropriate. In those situations it is best to turn off the AHU$_{\text{case}}$ and use the display case in a passive mode until the issues are resolved.

The display case climate conditions were also dependent on the exhibition gallery $T_{\text{room}}$ and RH$_{\text{room}}$ conditions. During handling of the museum items and opening the display cases the room conditions need to be as close to the display case conditions as possible to avoid sudden fluctuations. In practice, the gallery can be cooled down to $T_{\text{case}}$. Since the objects were placed in their own microclimates, RH$_{\text{room}}$ was allowed to fluctuate between the limits of 45–60%. Lowering RH$_{\text{room}}$ to 45% was more difficult to achieve in combination with the low $T_{\text{room}}$, resulting in a peak fluctuation.

### Table 2. Validation metrics for the 2D medium grid display case.

| Aim   | Range | 2D $k$–$\varepsilon$ | FAC 1.05 | MBE | CV | RMSE |
|-------|-------|-----------------------|----------|-----|----|------|
|       |       | coarse                |          |     |    |      |
|       |       | medium                |          |     |    |      |
|       |       | fine                  |          |     |    |      |
| $T_s,\text{plenum}$ | $T_s,\text{center}$ | $T_{\text{outlet}}$ | $T_s,\text{plenum}$ | $T_s,\text{center}$ | $T_{\text{outlet}}$ | $T_s,\text{plenum}$ | $T_s,\text{center}$ | $T_{\text{outlet}}$ |
|       |       |                       |          |     |    |      |
|       |       |                       |          |     |    |      |
|       |       |                       |          |     |    |      |
|       |       |                       |          |     |    |      |

![Figure 18. Simulation results of yearly imposed dynamic conditioning with ASHRAE climate class AA as $T_{\text{room}}$.](image-url)
in RH when the display case was opened (illustrated in Figure 9). These sudden fluctuations in RH
_case should be investigated further. Literature showed that due to the time it takes for an object to reach moisture equilib-
rium, the risk of degradation caused by fast fluctuations was limited. A timeframe for these fast fluctuations was often not given (Bigourdan and Reilly 2002). However, from previous literature it was known that the response time for paper objects or an opened book was in the range from hours to three days and a single sheet of paper responded within minutes. Books in tightly sealed cases had a response time of around 2–3 months. As a worst case, a response time of minutes was often used for paper objects (Michalski 1993; Ankersmit and Stappers 2016).

During experiment 5, T_room was increased to 24°C. The peak in T_inlet and T_case a few hours afterwards cannot be explained satisfactorily. The building management system did not account for an error or malfunction alarm but showed a temporary rise in cooling temperature which can be contributed to a short malfunction of the cooling system.

Experiment 7 involved cooling T_room back to 18°C in a time span of 18 h. The test showed that it was possible to cool back T_room to 18°C, however, it takes less than 2 h for the system to reach this set point. Maintaining the set point of 18°C consumed a significant amount of energy.

During the experiments it was noted that due to a low T_inlet, the RH of the airflow in the cavity is high (>60%). Though this airflow does not have direct contact with the displayed objects it might cause other types of inconvenience like condensation on the cold display case surfaces. During the experimental campaign attention was paid towards condensation issues although no cause for increased concern was noted based on measured values of temperature and relative humidity. However, it is recommended to keep monitoring the outlet conditions of the display case as well.

The main conclusions of this study are:

- From the experiments it can be concluded that T_case follows T_inlet closely. RH_case remains stable due to the almost airtight inner display case. This results in stable climate conditions where museum climate requirements are met in the inner display case.
- The novel display case design is able to generate a stable RH environment by means of silica gel, while using an active box-in-box climate control system to create stable and relative T conditions to increase collection lifetime.
- T_case depends on the AHU_case system. Protocols need to be in place in case of malfunction or failure of the climate control system. AHU_case needs to be shut off to create a passive environment for the objects on display. Experiment 5 shows that a sudden, unplanned rise in T_inlet provides unnecessary increased risks to the objects on display.
- Placing climate sensitive objects in display cases allows exhibition gallery control set points to be relaxed. Numerical modeling provides insight into the effect of dynamic simulation of T_room on the display case performance. It shows that relaxation of T_room setpoint does not influence T_case.

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No potential conflict of interest was reported by the authors.

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Appendix

Regular control setting (experiment 6)

While the $T_{room}$ conditions were set to 20°C the $T_{inlet}$ of the display case design should maintain a stable temperature of 17.5°C in the inner display case. This was the regular control setting that should be maintained throughout the year. Figure A1 provides the results of this experiment. As can be seen the $T_{a,case}$ is kept at a stable 17.5°C throughout the experiment. While the $RHa,case$ is too high, it shows stable behavior. To decrease the number of 65%RH towards the wanted 45%RH, silica gel is added in later experiments.

Calibration

During the measurement campaign it became clear that the requirement of no permissible fluctuations in the inner display case was a challenge to monitor. The Eltek data transmitters all have an accuracy of ±0.4°C and ±3%RH which, in this case, resulted in a large a spread. In order to decrease these numbers to be able to decrease the fluctuations noticed in this study, all transmitters were calibrated to such an extent that it removed the inaccuracy of the measurement equipment significantly. This appendix is divided in two parts. First, the temperature calibration is described, second, the relative humidity calibration is described.

Figure A2(a) shows the results of the imposed T trajectory in the climate chamber. The results compared the Eltek data transmitter including a Sensirion temperature sensor (object) with the reference sensor (Figure A2(b)). When the difference between Eltek and reference fall within the accuracy of the manufacturer the device was suitable for use. When more accuracy is wanted it is possible to make a correction by fitting the Eltek sensor data for T and RH to the reference sensor T and RH of which the accuracy was more precise. The Eltek sensor has a working range between −40 and 120°C. The investigated range for calibration lay between −10 and 40°C and the needed range for measurements was within 15–30°C.

In order to do this, the most constant period was determined by calculating in which window the two sensors showed the least amount of deviations. Figure A2(c) shows the results in which the green markers provide the constant period of the reference sensor and the magenta markers show the constant period of the Eltek sensor. The period where these markers overlap can be compared to each other. Since it was important to know that all periods weigh in equally, the smallest overlap was chosen (Figure A2(d)). In case of T, this resulted in a correction as presented in Table A3.
In order to fit the correction for values in between the tested calibration set points, a polynomial function was used (Equation (A1)).

\[ X_{\text{fit}} = B_2 \cdot X_{\text{object}}^2 + B_1 \cdot X_{\text{object}} + B_0 \]  

(A1)

**Figure A2.** Imposed temperature trajectory with results (a) and comparison (b) between Eltek sensor (object) and reference sensor. The constant period is calculated (c) to provide a number of overlapping matching measurements (d).
\( x_{\text{object}} \) is the variable \( T \) or \( RH \) of the sensor. \( x_{\text{fit}} \) is the corrected value for \( T \) or \( RH \). \( B_2, B_1, \) and \( B_0 \) are parameters used to fit the function. Figure A3(a) shows the measured reference sensor data (magenta markers) set out against the measured Eltek data and the correction function (grey line). \( s_{x_{\text{fit}}} \) is the accuracy standard deviation due to fitting.

The residuals were used to check if the correct polynomial function was used. The markers should be grouped around 0 to assume that the polynomial function was correct (Figure (b)).

Table A2 provides an overview of the parameters and statistical variables calculated for both \( T \) and \( RH \) correction. \( sB_2, sB_1, \) and \( sB_0 \) provide the standard deviation for the corrected variable. The uncertainty as result of the fitting was based on one times the standard deviation with a confidence interval of 68.3%.

**Figure A3.** Eltek and reference fitting by using polynomial function (a) and the residuals to confirm the correct use of this function (b).

**Table A1.** Temperature calibration correction; average value of 44 measurements per imposed set point.

| \( \theta_{\text{ref}} \) [°C] | \( \theta_{\text{object}} \) [°C] | \( \theta_{\text{correction}} \) [°C] |
|----------------|----------------|----------------|
| –9.92          | –8.90          | –1.02          |
| 0.10           | 0.84           | –0.74          |
| 10.10          | 10.50          | –0.4           |
| 20.22          | 20.31          | –0.08          |
| 30.36          | 30.20          | 0.16           |
| 39.75          | 39.41          | 0.34           |

**Table A2.** Polynomial parameters for \( T \) and \( RH \) of the sensor used in inner display case 1.

|   | \( B_2 \)  | \( B_1 \)  | \( B_0 \)  | \( sB_2 \) | \( sB_1 \) | \( sB_0 \) | 1*\( s_{x_{\text{fit}}} \) | \( R^2 \) |
|---|---|---|---|---|---|---|---|---|
| \( T \) | –0.00016787 | 1.034 | –0.7301 | 1.1e–005 | 0.00037 | 0.0035 | 0.036°C | 1.0 |
| \( RH \) | 0.00087202 | 1.0689 | –11.67 | 6.2e–005 | 0.0082 | 0.25 | 0.47% | 0.9995 |
Table A3. Relative humidity calibration correction; average value per set point.

| RH_{ref} [%] | RH_{object} [%] | RH_{correction} [%] |
|--------------|-----------------|---------------------|
| 45.20        | 50.30           | −5.1                |
| 66.97        | 69.11           | −2.1                |
| 88.08        | 86.73           | 1.3                 |
| 46.05        | 51.82           | −5.8                |
| 67.40        | 69.89           | −2.5                |
| 87.79        | 86.92           | 0.87                |
| 35.43        | 42.50           | −7.1                |
| 45.73        | 51.64           | −5.9                |
| 67.31        | 70.53           | −3.2                |
| 90.44        | 88.85           | 1.6                 |
| 30.26        | 38.33           | −8.1                |
| 45.98        | 52.10           | −6.1                |
| 70.60        | 72.98           | −2.4                |
| 90.06        | 89.13           | 0.93                |

Figure A4, Table A3, and Figure A5 provide the relative humidity calibration results. The steps correspond with the above described temperature calibration method.

Figure A4. Imposed relative humidity trajectory with results (a) and comparison (b) between Eltek sensor and reference sensor. The constant period is calculated (c) to provide a number of overlapping matching measurements (d).
Figure A5. Eltek and reference fitting by using polynomial function (a) and the residuals to confirm the correct use of this function (b).