Climate Stability of Historical Museums: Research of Temperature and Moisture Reaction in Areas Close to Outer Walls— Consequences Regarding the Building and the Exhibits

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ABSTRACT

In the range of the modernization and restoration of the Herzog-Anton-Ulrich Museum of Brunswick, the differences between the climate near the exterior wall and that of the average room-climate were measured.

In addition to that, the risk of damages at the building fabric caused by moisture and the conservative risk of the exhibits fixed at the inner side of the exterior walls were evaluated.

Regarding the mathematical description of the heat-transfer circumstances and flow circumstances at the area near the exterior walls, the determination of the convective heat-transfer coefficient at the boundary areas of wall and exhibit to the air gap is not clearly soluble. Usually the affinity theory can be used when having free convection circumstances.

In the above-mentioned case there is a thermally affected output stream at the cold wall as well as a forced convection that is due to the ventilation and heating system.

For this application, in particular regarding the airspeed and the gap's geometry, there are no authentic similarity models known. As a result, it is only possible to get an approximate appointment of the heat-transfer procedure by calculating.

Temperature and moisture measurements on the objects' surfaces were carried out in addition to the theoretical analyses to evaluate the conservative and physical risk of damage regarding the precise case of a picture gallery. In addition to that, the heat and airflow in the range of the exhibits that are fixed at the inner side of the exterior wall have to be analyzed via numerical simulation.

INTRODUCTION

First and foremost, the fixation of the room climate in spaces that are used as exhibition halls is motivated by preservation criteria. Especially in art galleries, demands of the preservation climate only allow an extremely limited variation as far as room air temperature and relative room air humidity are concerned. Particularly, the breadth and the quantity of variation of the relative room air humidity have considerable influence on the aging process of the exhibits and can ultimately damage them.

In practice, the planners generally start from the idea that there is *one* room temperature as well as *one* relative room air humidity. The prevailing degrees of moisture are measured in the area of the discharged airstream or somewhere else in the room. Often, however, the areas more difficult to preserve, e.g., areas where problems may arise due to existing outer walls or ventilation systems, are not taken into account and, consequently, lead to cases of damage although the room's climatic conditions seem to be acceptable.

Besides the question of to what extent the climate in areas near the outer walls differs from the climate in the middle of the room, the question of to what extent there is a risk of damage(s) due to humidity increase with regard to the building materials, as well as the exhibit itself, also has to be answered. As far as the professional group of restorers is concerned, all the processes and phenomena that are related to this problem are classified under the term of the *cold-wall-problem* (Ranacher 1995).

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CALCULATION OF THE TEMPERATURE REACTION OF OUTER WALLS COVERED WITH EXHIBITS

In order to obtain a general applicable assessment of the influence of exhibit-covered outer walls on the heat storage and temperature reaction both of the outer wall and also the different layers of material of a painting, it is necessary to record the thermally caused air current between the wall covering and the reverse side of the painting, which depends upon the geometrical and thermal marginal conditions.

The transfer of heat between the reverse side of the painting and the front side of the wall takes place by transmission, convection, and radiation (Figure 1). Thus, the following model of a heat balance can be drawn up.

Transforming the above-mentioned complex process of heat transmission into an energy balance, one obtains a nonlinear ninth-grade equation. The solution of the energy balance with regard to the system *painting–air layer–cold exterior wall* leads to the following processes:

- Heat radiation from the reverse side of paintings in the direction of the cold wall. The intensity of the heat radiation increases as much as the outer wall's inner surface gets colder.
- Convective heat output from the reverse side of the paintings to the air gap and convective transfer to the outer wall. The intensity of the heat convection increases as much as the outer wall's inner surface gets colder and the air current in the air gap intensifies. As far as the air current itself is concerned, it intensifies equally together with the decreasing temperature of the inner surface of the outer wall.
- Furthermore, the unhindered, purely thermally caused convection is additionally superpositioned by a forced convection that comes from the ventilation system or the air heating installation.
- Both processes of heat transmission lead to a cooling of the reverse side of the painting and a warming of the inner surface of the outer wall, whereas the latter effect is rather marginal due to the high heat storage capacity of the wall.

In the sequence from the air gap at the front side of the painting to the outer side of the outer wall, one cannot assume a constant density of heat current q since a convective heat exchange takes place between the above-mentioned system and its surroundings. The difficulty lies in the determination of the convective coefficient of the heat transfer h_{cv}. Describing the heat transfer between the surface of the building material or the surface of the painting and the air gap, this coefficient depends on a variety of changeable factors, especially temperature, speed, viscosity, and heat conductive capacity and the kind of air current in the gap as well as on the geometry, temperature, and roughness of the surface of the solid body. Coefficients of the heat transfer have to be determined by carrying out experiments and can be generalized with the help of the theory of similarity.

In order to assess the thermal reaction in this area, the temperatures above the cross section of the compound unit were calculated with different suppositions and compared with the measurements (also compare the experiments that were carried out in the HAU, chapter 3).The following calculated or measured data served as the starting parameters:

- The exterior temperatures ϑ_α are changed in the range from –15°C to 10°C in five K-steps.
- Maintaining an indoor range of temperature from 18°C to 20°C is demanded (BBS Institut 1999). At the same time, calculations are carried out in the case of a failure of the air-conditioning during wintertime (ϑ_ι = 13°C).
- The temperature in the gap between the wall and the painting is on average 1 K below the room temperature (result of the experiment).
- As far as the coefficient of the transfer α_k is concerned, for an analysis of the measurement data and the solution of the equation system, the value $a = \alpha_k = 2.26$ was determined. In order to take account of the dispersion of data, the following cases, $a = \alpha_k = \alpha_k\,[2.26] + 3$ und $a = \alpha_k = \alpha_k\,[2.26] - 3$, were examined.

In addition to the wall temperature ϑ_W and the surface temperature of the protective layer of the reverse side of the painting ϑ_O, the surface of the front side as well as the reverse side ϑ_{Bv} and ϑ_{Br} of the painting's layers are calculated. As a comparison, the case of the "standing air space" is looked at.

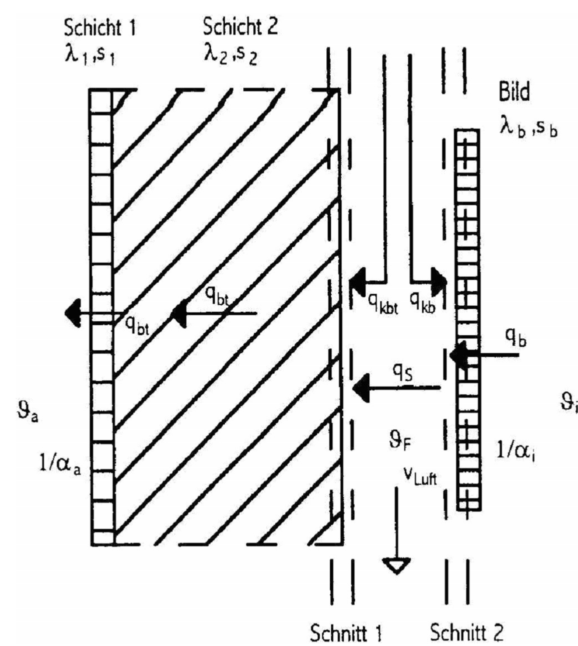

Figure 1 *Heat currents in the system* wall-air gap-painting.

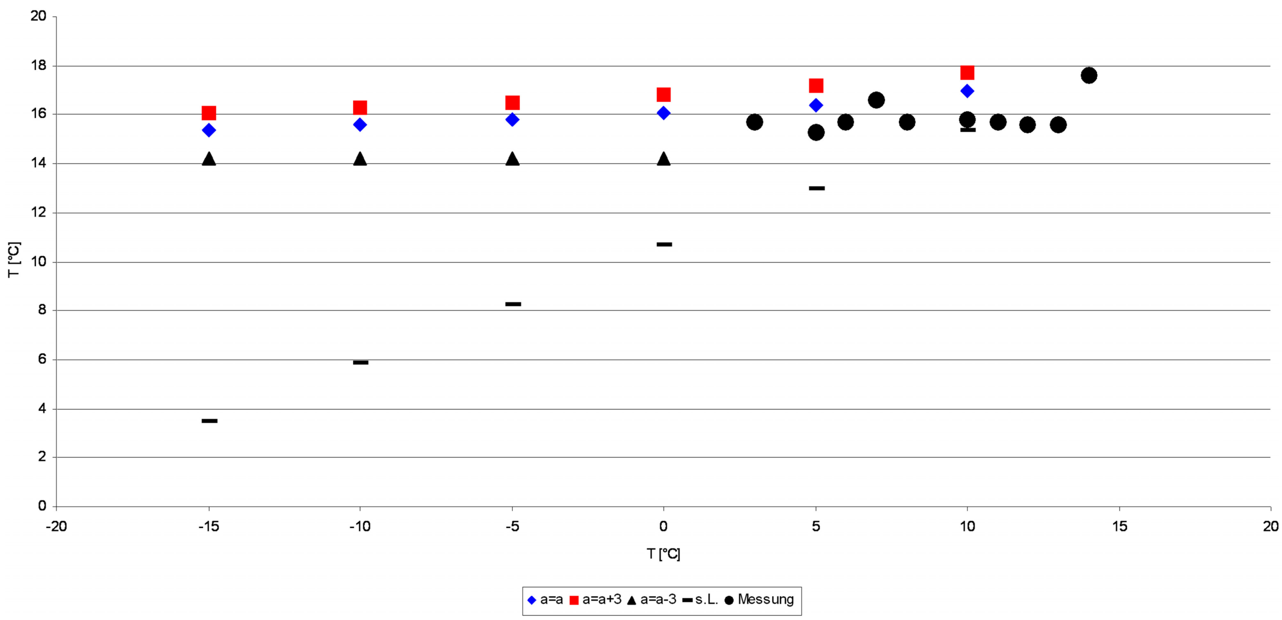

Figure 2 *Temperatures of the surface of the wall ϑ_W with an indoor temperature ϑ_i of 20°C.*

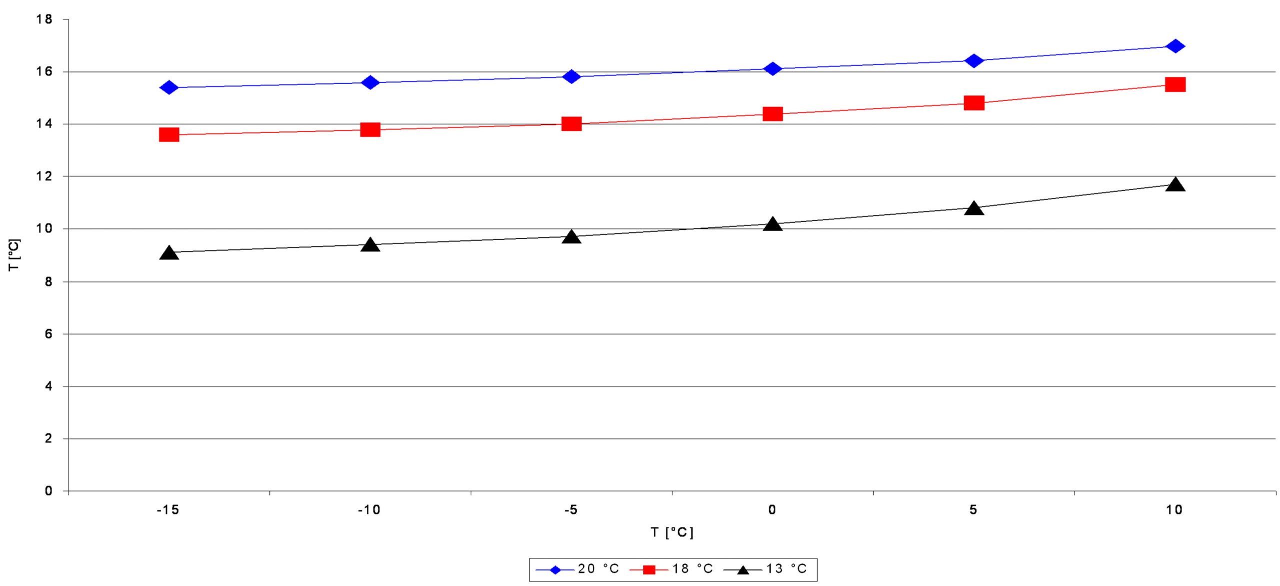

Figure 3 *Temperatures of the surface of the wall ϑ_W with different indoor temperatures ϑ_i.*

Figures 2 and 3 illustrate the comparison of the measured temperatures together with the calculations' results.

MEASUREMENTS OF THE LIMITING LAYER OF TEMPERATURES OF A PAINTING HANGING ON THE OUTER WALL

The measurements were carried out at the painting *Nymphs and Satyrs* by Louis de Silvestre (1675-1760) in the so-called *French Hall*, a northern side gallery in the first floor of the Herzog-Anton-Ulrich Museum in Brunswick.

The painting hanging in front of the outer wall consists of the following elements (beginning with the reverse side, Figure 4):

- protection of the reverse side made of cardboard (d = 0.5 cm)
- wedge frame (d = 3.5 cm)
- double canvas

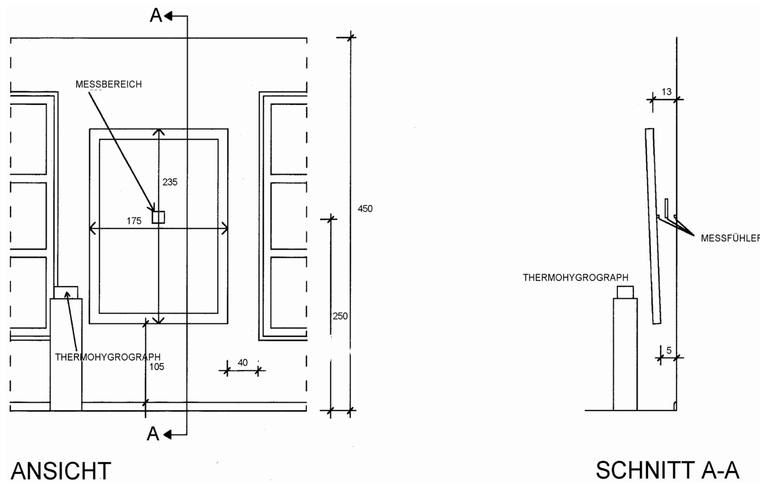

Figure 4 *Setting up of the measurement equipment in the area of the painting in the French Hall.*

- priming coat
- coat of paint
- layer of oil-varnish

The painting is not glazed and there are separators at the reverse side of the painting (distance on top, 13 cm; at the bottom, 5 cm).

Comparative measurements were carried out in an undisturbed wall area in a room that is used as a restoration workshop in the northern side gallery on the first floor.

Figures 5 and 6 show the results of the temperature measurements (duration: November 10-December 1, 1999) in the *French Hall* and the restoration workshop.

The analysis of the temperature measurement show

- the difference of the painting's surface temperature, which is decisive regarding the stress on the painting, is 2 K on average;
- the difference of the exterior wall's surface temperature, which is decisive regarding the safety of the building construction, is 4 K on average; and
- the difference of the exterior wall's surface temperature, which is also decisive regarding the relative air humidity in the air gap, is 1 K on average below the normal room air temperature.

The effects of the temperature differences concerning the relative air humidity and, consequently, the sorption as well as the shrinkage and swelling behavior of the paintings, are explained later in the paper.

MEASUREMENTS OF THE RELATIVE AIR HUMIDITY OF THE HERZOG-ANTON-ULRICH MUSEUM

Not only the temperature, but also the relative air humidity were recorded in the period of November 10-December 1, 1999 (Figure 8), in line with the technical measurement analysis. Figure 7 shows the conversion of the relative humidity into the absolute air humidity.

THE DANGER OF CONDENSATE AT THE EXHIBITS FIXED ON THE EXTERIOR WALLS

To make a statement regarding the danger of condensate to the exhibits at the exterior walls of the Herzog-Anton-Ulrich Museum, the walls' surface temperatures ϑ_{wall} and the paintings' back sides $\vartheta_{painting}$ in the crack have to be compared with the temperature of dew point $\vartheta_{dew\ point}$, which can be calculated with the help of the rooms' ambient data.

The aim of all building climatic tasks in museums is compliance of the room air temperature and the room air humidity with following data:

- room air temperature ϑ_i: 18-20°C
- room air humidity φ_i: 50-55% relative humidity (RH)

These data are based on following dew-point temperatures:

1. Normal case $\vartheta_{dew\ point\ (dp)}$ (18°C, 60% RH) = +10.1°C
2. Normal case $\vartheta_{dew\ point\ (dp)}$ (20°C, 60% RH) = +12.0°C
3. Collapse of the air conditioning $\vartheta_{dew\ point\ (dp)}$ (13°C, 80% RH) = +9.6°C

Table 1 shows the comparison of the dew-point temperature and the surface temperatures concerning to different heat-transfer coefficients.

The comparison of the dew-point temperature and the surface temperatures points out that there is no danger of condensate arising at the walls' surface as well as at the paintings' back sides when having a controlled operation. The minimal differences between the surface and the dew-point temperature with regard to the different assumptions of the convective heat-transfer coefficient α_k in the gap are at least 2 K at the walls' surface and at least 4 K at the paintings' backside.

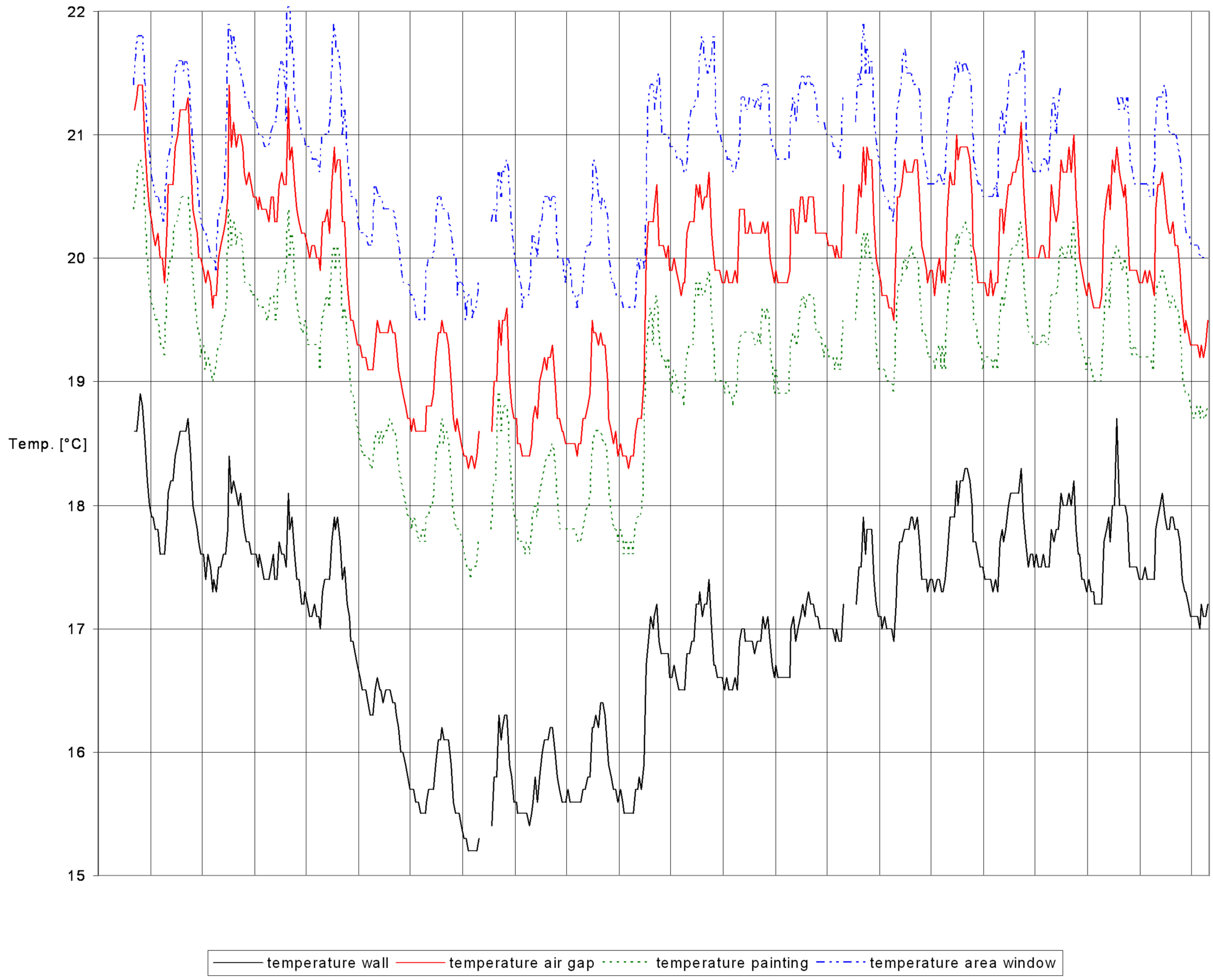

Figure 5 *Temperature gradient in the painting's area—French Hall.*

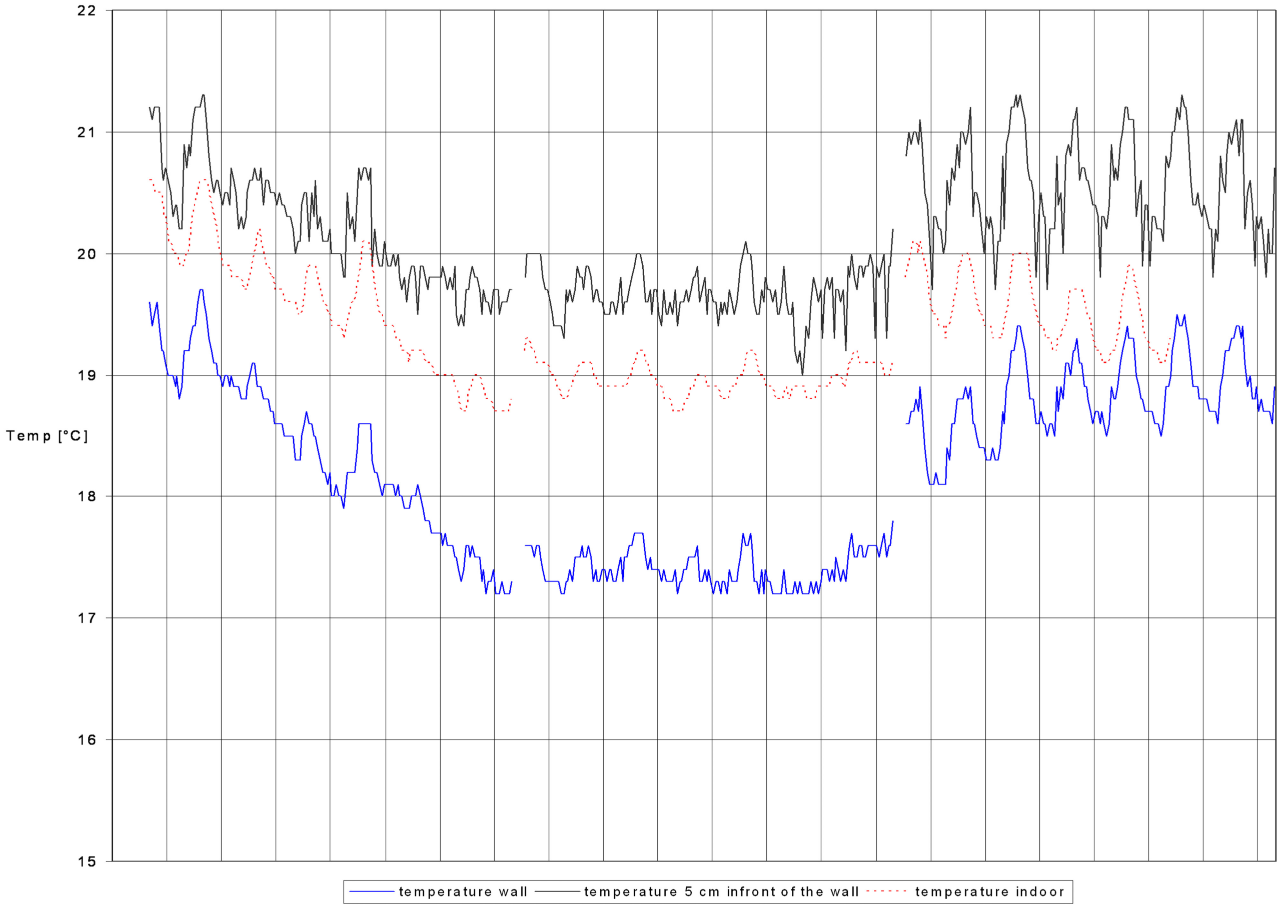

Figure 6 *Temperature gradient in the undisturbed area—restoration studio 1.*

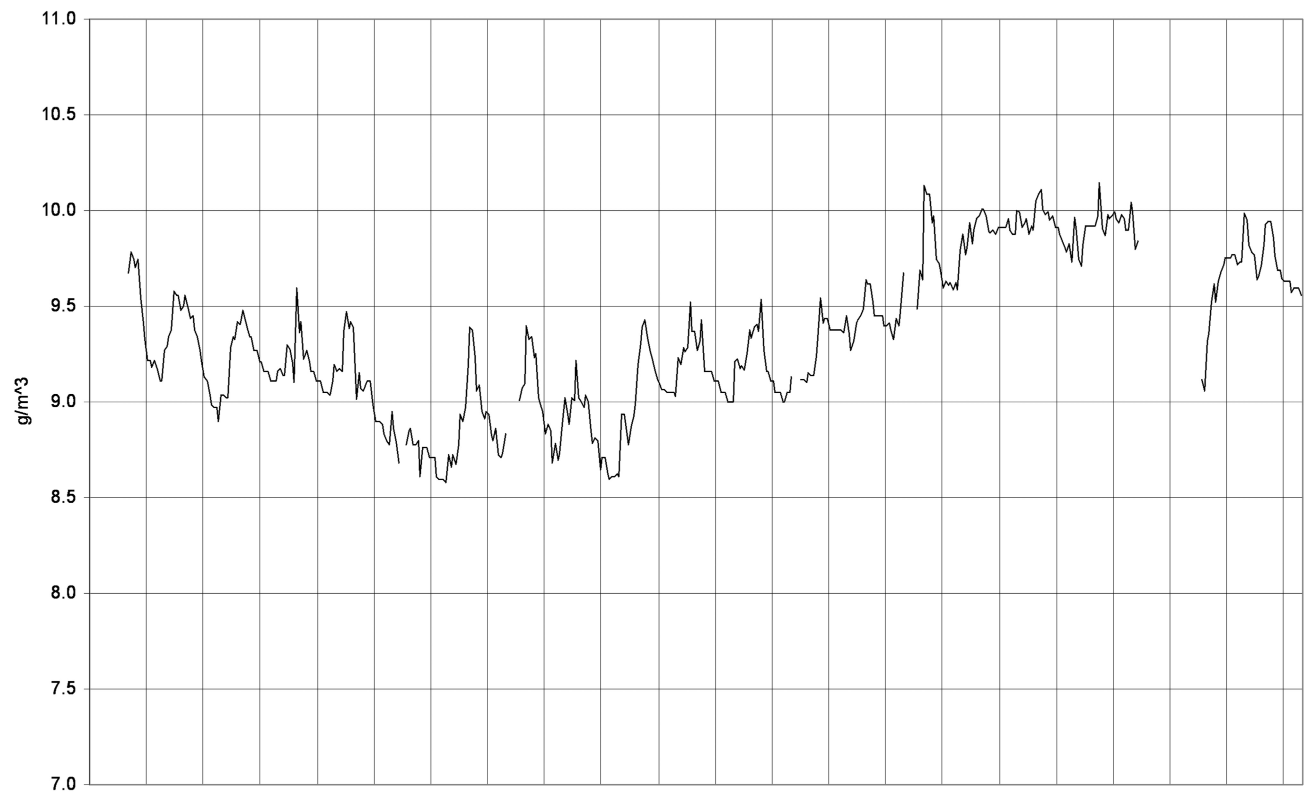

Figure 7 *Absolute air humidity in the French Hall.*

Table 1. Differences Regarding the Surface and Dew-Point Temperatures at a Controlled Operation and an Event of Fault

	ϑ_i [°C]	$\Delta (\vartheta_{Wall} - \vartheta_{dp})$ [K]	bei ϑ_a [°C]	$\Delta (\vartheta_{painting} - \vartheta_{dp})$ [K]	bei ϑ_a [°C]
$\alpha_k = \alpha_k$ [2.26]	18.0	3.5	–15.0	6.1	–15.0
$\alpha_k = \alpha_k$ [2.26] + 3	18.0	4.1	–15.0	6.4	–15.0
$\alpha_k = \alpha_k$ [2.26] - 3	18.0	2.4	–15.0	5.0	0.0
$\alpha_k = \alpha_k$ [2.26]	20.0	3.4	–15.0	6.1	–15.0
$\alpha_k = \alpha_k$ [2.26] + 3	20.0	4.1	–15.0	6.4	–15.0
$\alpha_k = \alpha_k$ [2.26] - 3	20.0	2.2	–15.0	4.8	–15.0
$\alpha_k = \alpha_k$ [2.26]	13.0	–0.5	–15.0	1.8	–15.0
$\alpha_k = \alpha_k$ [2.26] + 3	13.0	0.1	–15.0	2.0	–15.0
$\alpha_k = \alpha_k$ [2.26] - 3	13.0	–1.5	–15.0	1.2	0.0

The collapse of the air conditioning (room climate: 13°C, 80% RH) provokes a shortfall of the dew-point temperature and, consequently, rising condensate on the wall's surface, but there was no condensate on the exhibit itself at each calculated case.

CONSIDERATION OF THE PAINTINGS' LOADING CAUSED BY SHRINKAGE AND SWELLING

The sorption attribute of the materials affects shrinkage and swelling. Here the material absorbs and releases the moisture as a consequence of the changing relative air humidity. This changing volume finally causes the aging of the exhibits.

The basis of all HLT regulations regarding climate stability and, consequently, the assurance of the exhibits in museums, is the room humidity! This humidity is measured either near the discharged airstream or somewhere else in the room. The relative air humidity is the basis of arrangements and assessments. This measured humidity extensively differs from the humidity that can be recognized in the range of the drawings, which are fixed on the exterior walls. Consequently, the

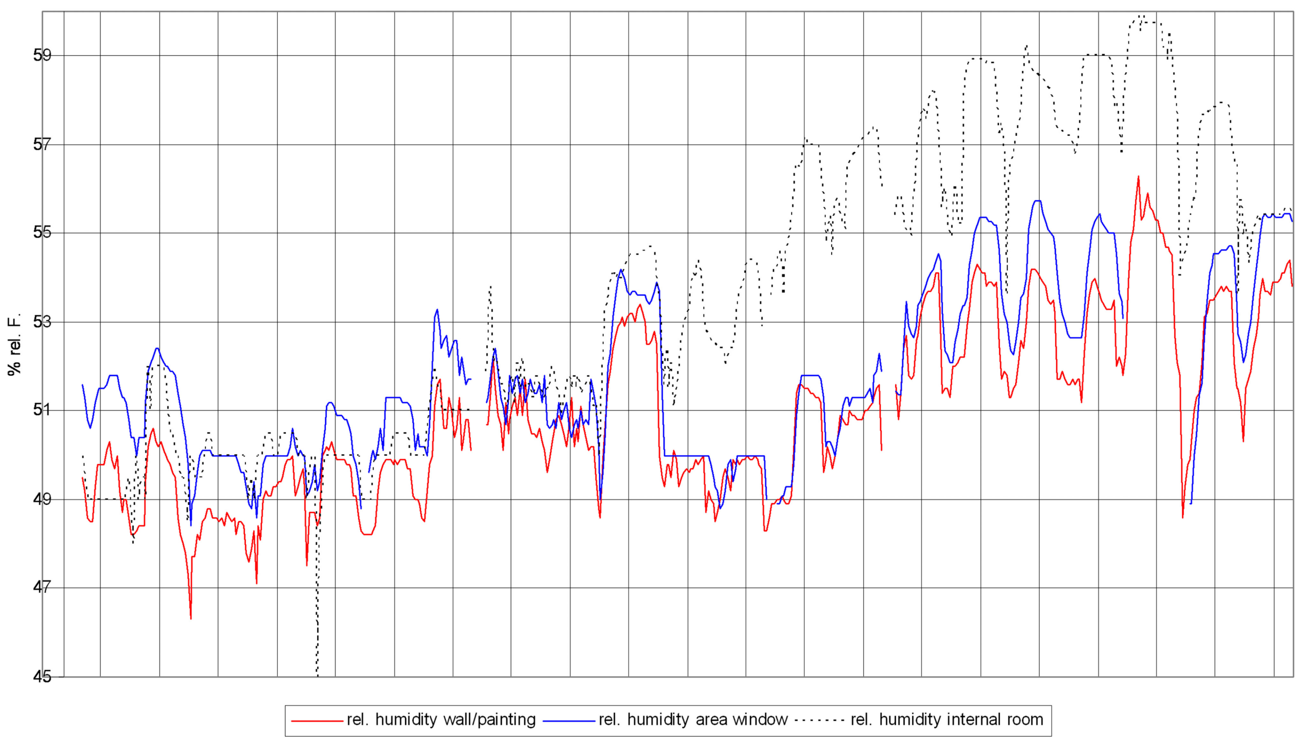

Figure 8 *Measurements of the relative air humidity of the French Hall from November 10 to December 1, 1999.*

HLT regulations have to be carried out on the basis of these measurement of the relative air humidity in the described area!

RESULTS

At first, the following climatic connections in the air gap can be acquired based on the measured air and surface temperatures as the air humidity in the gap and in the room are connected with different versions of calculations.

The connection between the outside temperature and the convective heat transfer coefficient in the air gap is approximately linear.

- A comparison between the surface temperatures with the dew-point temperature in the air gap shows that the inner wall surface's temperature is at least 2 K and the surface temperature of the painting's backside is at least 4 K greater than the dew-point temperature of the bordering air layer.
- The absolute air humidity in the air gap and in the room air is nearly equal. Consequently, there is no damp diffusion sloping at the boundary areas of the exhibit. So the intensity of the air circulation in the gap is great enough to prevent so called "Klimataschen."
- The air temperature in the space between the exterior wall and the back side of the exhibit is approximately independent to the outside temperature and is on average 1 K lower than the room temperature. This can be explained by the fact that, on the one hand, the heat storage capacity of the massive exterior wall causes a significant amplitude damping of the (from outside) penetrating temperature radiation and, on the other hand, the interior wall surface's cooling strengthens the thermal conditioned air current. Consequently, the convective heat supply of the room air into the air gap is strengthened, too. So the outer temperature and the convection almost compensate for each other.
- The difference of the painting's back side and front side is maximal at 0.3 K. With the conditions $\phi_i \approx 20°C$ and $\varphi_i \approx 50\%$ RH, the humidity difference is about $\Delta\varphi_i \approx 1\%$ RH.
- Only a malfunction of the air conditioning, not a changing condition of the outside weather, is able to cause a temporary variation of the temperature and, in consequence, of the relative humidity.
- The basis of all HLT regulations regarding climate stability and, consequently, assurance of the exhibits in museums, is the room humidity! This humidity is measured either near the discharged airstream or somewhere else in the room. The relative air humidity is the basis of arrangements and assessments. This measured humidity extensively differs from the humidity that can be recognized in the range of the drawings, which are fixed on the exterior walls. Consequently, the HLT regulations have to be carried out on the basis of these measurement of the relative air humidity in the described area.

A hygric thermal decoupling is crucial to not have durable damage of exterior wall constructions and the exhibits. This can be reached if sufficient air circulation in the gap between the exterior wall and the exhibit can be reached. This air circulation has a more positive effect if the gap is greater: $x_L \geq 0{,}02\ H^{2/3}$ (with x_L = gap width and H = painting's height) is a recommendation of Petzold (1980). This connection between the gap's width and the painting's height could be confirmed in the received case. Additional methods to improve the conservatory comforts are, e.g., to fix a heat insulation layer on the exhibit's back side and/or to increase the inner wall surface's temperature. This can be reached with the help of heat insulation or a wall heating system.

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