Influence of New External Protective Glazing on Historic Painted Windowpanes in Medieval Churches

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ABSTRACT

In an effort to protect interior painted glass windows (not colorful stained glass) in medieval churches against climatic and mechanical attack, an additional glazing was installed on the exterior at a given distance to the existing glazing. To determine whether this action may threaten the paint in any way, various sensors were installed at specific places around one window each at the upper northern and southern windows of St. Mary's church in Rostock, Germany, while general restoration work was in progress and the necessary scaffolding was available.

Hourly data of the 32 sensors were collected over one year and then supplemented by the climate data of a nearby national weather station. Collection of data will continue.

The results of the measurements show that natural convection exists in the space between the glazings. This space is equipped with apertures at the bottom and top and ventilated towards the indoor climate, depending on the exterior temperature and solar radiation. Short-time condensation occurs at both sides of the interior glazing. After the test period, only a few microorganisms were found on the paint.

The investigation indicates that it is essential to ventilate the space between glazings with upper and lower gaps, but to the inside rather than to the outside (as is usual with ventilated facades). The outside protective glazing has to be airtight.

INTRODUCTION

St. Mary's Church is the largest of four medieval churches of the Hanse-Town Rostock, situated in northern Germany at the coast of the Baltic Sea. The church was first mentioned in the middle of the 13th century and was under construction for more than 200 years in different stages. In 1398, the Gothic building began to be transformed into a cruciform three-nave basilica. The Gothic windows' colorful glazings were placed above the side naves and above the choir (Jeremias 2007; Nath 2007), as shown in Figures 1 to 3.

To protect these artworks against aging and mechanical impact, an exterior pane of clear glass was installed with a spacing of 80 mm (3 in.). The top and bottom interior glass elements were inclined as shown in Figure 4, so the clearance between glazings has contact to the interior air. At the bottom of the clearance, a flat lead tray collects incoming rain and conducts it through a tiny opening to the outside (Figure 5).

During the centennial general restoration of the church, which is 33 m (100 ft) high inside at the middle nave, interior and exterior scaffolding was available for restoration of the glazings and the addition of the monitoring program. This research program should determine whether the influence of the outside glazing may cause condensation on the paint and how to prevent it. The condensation itself will not damage the painted surface, but acidic secretions of microorganisms growing in the condensed water will damage it.

It is important to note that the church is neither heated in winter nor air conditioned in summer.

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Figure 1 *Southeast view of St. Mary's church, Rostock.*

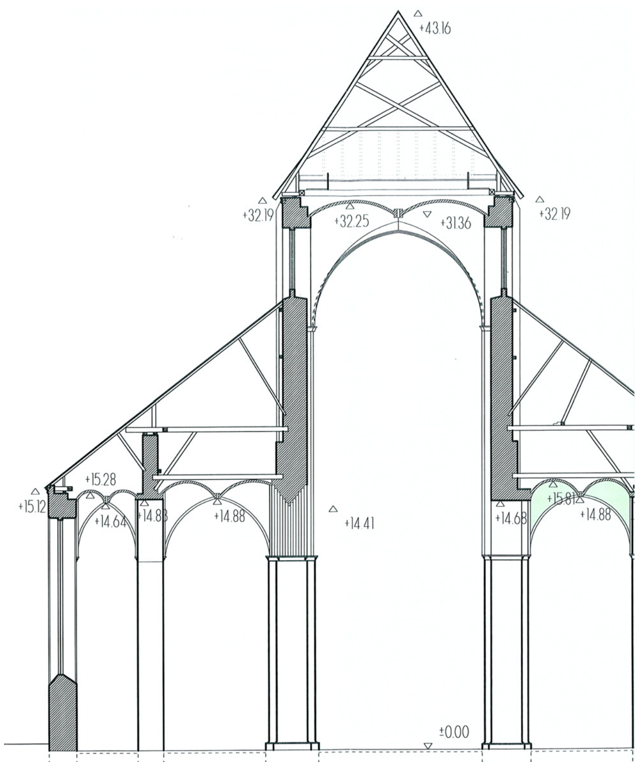


Figure 2 *Southern choir window outside (protective glazing).*

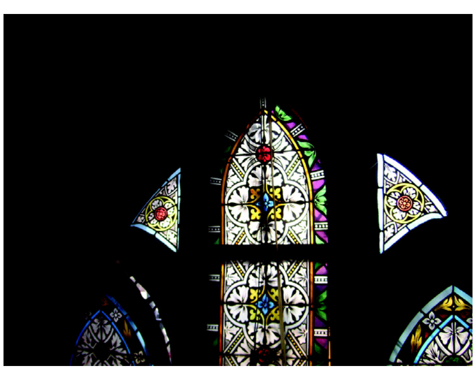


Figure 3 *Choir window, painted interior glazing.*

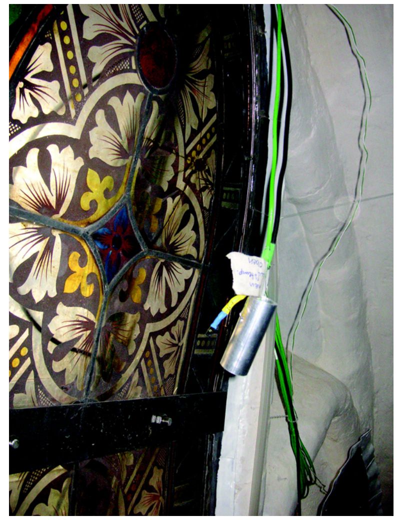


Figure 4 *Sensors inside: thermocoupler capsuled against radiation and relative humidity.*

Figure 5 *Sensor for humidity on the lead tray.*

APPROACH

Due to the availability of scaffolding inside and outside along the walls for the restoration project, a research program was funded by the Deutsche Stiftung Umweltschutz (German Foundation to Protect Environment) to prove the efficiency of the clearance between the glazings to protect the paint. Therefore, four questions related to the humidity in the clearance space and the condensation on both sides of the painted glass should be answered by these investigations (Mainka and Winkler 2007).

1. **How tight is the exterior glazing? Does rainwater penetrates the outer glazing?** There are two types of joints:
    - Between individual painted glass pieces connecting to each other and/or to the steel frame. The connecting material is lead.

- Gaps between window and wall. These were tightened traditionally by a hemp rope and were closed inside and outside by mortar. Pieces of mortar have dropped out within the last 20 years, so on top of the new mortar outside a new flashing of lead tin was developed, which was soldered to the window frame and pressed to the wall, as shown in Figure 5.

The air infiltration rate was tested directly after restoration.

2. **Does ventilating the clearance space to the inside of the church lead to increased humidity and condensation?** Different temperatures between inside and outside as well as solar radiation lead to thermal convection (up or down) within the clearance and cause an air exchange between the clearance space and the interior air of the church.
3. **Does humidity from the walls influences the humidity in the clearance space?** Wet walls may cause evaporation into the clearance space and increase the humidity.
4. **When and how long is water retained on both sides of the painted glasses?** Microplants and fungi need water to start growing and allow microanimals to live. Different temperatures favour the growth of certain types of microorganism.

MEASURING CONCEPT

Analysis of Microorganisms

One of the painted window elements (about 400 mm × 400 mm) was screwed out of the window frame, cleaned, and reinstalled. After one year, when the scaffold had been removed, a mountain climber took out this element again, which was then investigated in a lab for the presence of microorganisms and their types.

Short-Time Investigations Concerning Airtightness of the Windows

First qualitative investigations were made by ultrasound with the sender inside and receiver outside. Leakages were marked and rebuilt.

Better results were obtained by a modified blower-door test. Because of the enormous size if the church a foil coated over the window to the wall created a test-volume. For qualitative assessment, artificial fog was blown with the Blower Door fan into the wrapping. Very little fog penetrated the joints of the exterior window, mainly through the joint to the wall which could be observed outside.

Quantitative tests were also made with the modified blower-door method with depression. Because the fan of the blower door was too strong, it was replaced by a hair dryer. Finally, because there is no relevant house volume, the measured air flow was related to the length of the window/wall joint according to the test of window joints (*DIN Standard 4108-7:2001*; *DIN Standard EN12 207:2000*).

The length-related flow resistance a_f can be calculated by

$$a_f = V' / (l\,\Delta p^{2/3}) \qquad \text{in m}^3/(\text{hm·Pa}^{2/3}) \qquad (1)$$

where

V' = air stream, av, m^3/h
a = inlet/outlet area, m^2
v = air speed, m/h
l = length of joint, m
Δp = air pressure (difference), Pa

With l = 11 m and different air pressures Δp, the average value of a_f is 0.1 $m^3/(hm·Pa^{2/3})$, a very good value compared to those in residential houses (maximum a_f= 1 $m^3/[hm·Pa^{2/3}]$).

Calibration of Hygric Sensors for Walls

The electric resistance method is not sufficiently precise for measuring humidity in mineral materials. Therefore, at the wall beside the window, the air humidity was measured in a borehole. The interaction between humidity in material and humidity in the adjacent air can be obtained by sorption isotherms of little material samples measured at different temperatures in a lab.

Long-Time Measurements

To record the long-time thermal and hygrical behavior of the windows over a period of one year, hourly measurements were made at one northern and one southern top window for air and surface temperatures, humidity, air velocity, air pressure differences and water detection at different locations.

Measurements were taken from June 2006 to June 2007. In total, 2 × 29 automatically registering and 1 monthly manually reading sensors were installed, for a total of 59 sensors (Table 1).

Climate Data from Weather Station

Supplementary data from the nearby official weather station at Rostock-Warnemünde (distance: 12 km) were integrated with our own data analysis for temperature, relative air humidity, wind speed and direction, solar radiation, and rainfall (DWD 2007).

MEASURING INSTRUMENTS AND LOCATION OF APPLICATION

Sensors and Data Logger

At the northern and southern choir windows, the following sensors were installed (see Table 1 and Figure 6).

The exterior and interior air sensors (θ, Φ) were installed 100 mm (4 in.) in front of the windows on iron rods. Sensors in the middle of the clearance (air) (θ, Φ, v, Δp) were fixed on vertical nylon strings. Thermocouples (θ) were coated on glass surfaces with water-resistant tape. The water detector

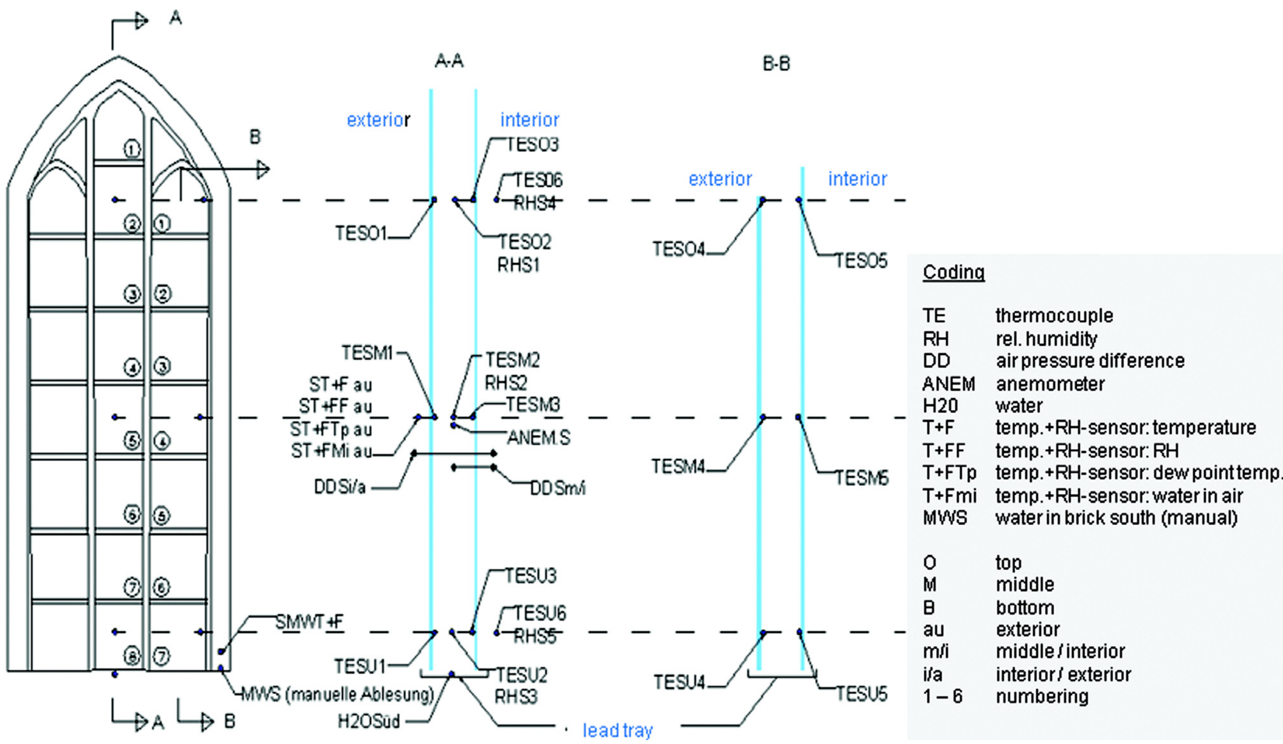


Figure 6 *Locations for sensors.*

Table 1. Sensors at a Choir Window

Measuring Unit	Symbol	Unit	Tensor Type	Number	Location
Temperature Relative air humidity ➔Material humidity	θ Φ ➔*u*	°C % kg/kg	Pt 100 Electric capacity Sorption isotherm	1 1	Exterior wall borehole (only south window)
Air pressure differences	Δ*p*	Pa	Membrane	1 1	Clearance–interior, interior–exterior
Air velocity/speed	v	m/s	Propeller anemometer	2	Clearance
Water detector	w	yes/no	Electric resistance	1	Clearance bottom
Temperature	θ	°C	Thermocouple	2 × 3 2 2 × 3 3	Clearance exterior glass Clearance middle air Clearance interior glass Interior air
Relative air humidity	Φ	%	Electric capacity	3 2	Clearance middle air Interior air
Material humidity	u	kg/kg	Electric resistance (manual)	(1)	Wall clearance bottom
Total				29+(1)	

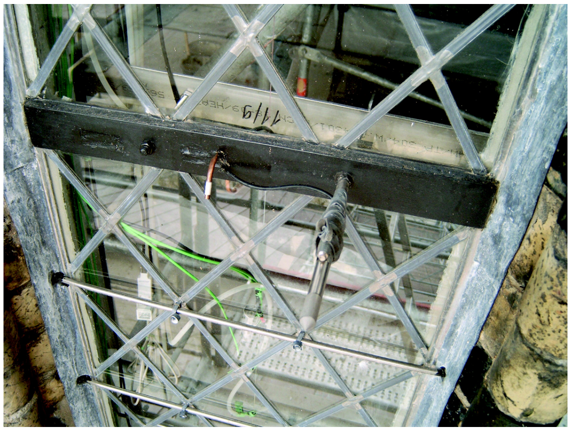


Figure 7 *Sensors outside. Right: temperature and relative humidity; left: pipe outlet for air pressure difference.*

(w) was fixed in the lead tray and insulated against the metal. (see Figures 4, 5, and 7).

The cables were bundled and led vertically upwards inside the church through ventilation openings to the top of the arch, where they were connected to the data logger from the Ahlborn Company (Ahlborn 2006). The programmable connectors of the different sensors were conditioned to their characteristics (type, unit, calibration) so that the data logger recognized a sensor automatically when plugged in. The data logger was linked to a PC to store the data onto a hard disk. To prevent possible data losses due to power cuts, an electric buffer was installed and the PC equipped with an automatic restart after longer interruptions. For further measurements, a laptop instead of the PC was provided. Every month, the system was serviced and the collected data stored extra on a USB flash drive.

The data was logged hourly and processed in Microsoft Excel format.

MEASURING RESULTS

The vast amount of data was handled and visualized in different steps.

Yearly Time Variation Graphs

For each sensor, an annual time variation graph showed

- Time of malfunction
- Range and number of yearly, monthly, and daily oscillations
- Comparisons of similar sensors (north/south, height, inside/outside) to identify characteristics, or skip a sensor for further analysis
- Choose relevant months, days, or periods for precise analysis

Because some of the measured data oscillated daily, the yearly time variation graph shows a broad band in which only the peaks can be recognized. For better interpretation, the time-dependent data were separated into groups for each hour of the day. Values for 00:00 h, 06:00 h, 12:00 h, and 18:00 h were plotted in their own graphs. Figure 8 shows the effect for ventilation in the clearance.

Monthly Time Variation Graphs

This presentation allows us to compare several similar graphs on one sheet and to interpret interdependences.

- Air pressure differences: wind directions and speed
- Air velocity in the clearance: solar radiation from the nearby weather station, as shown in Figure 9
- Air temperature inside, at the clearance, and outside at different heights

Daily Time Variation Graphs

To address the problem of condensation, the daily graphs have been analyzed with regard to the risk of condensation, temperature, and thermal buoyancy in the clearance as well as air humidities and partial vapor pressures inside, outside, and in the clearance for the following five days (Table 2).

The wind speed in the clearance and the different temperatures for 2006-08-30 are shown in Figure 10.

Dropout of Condensate

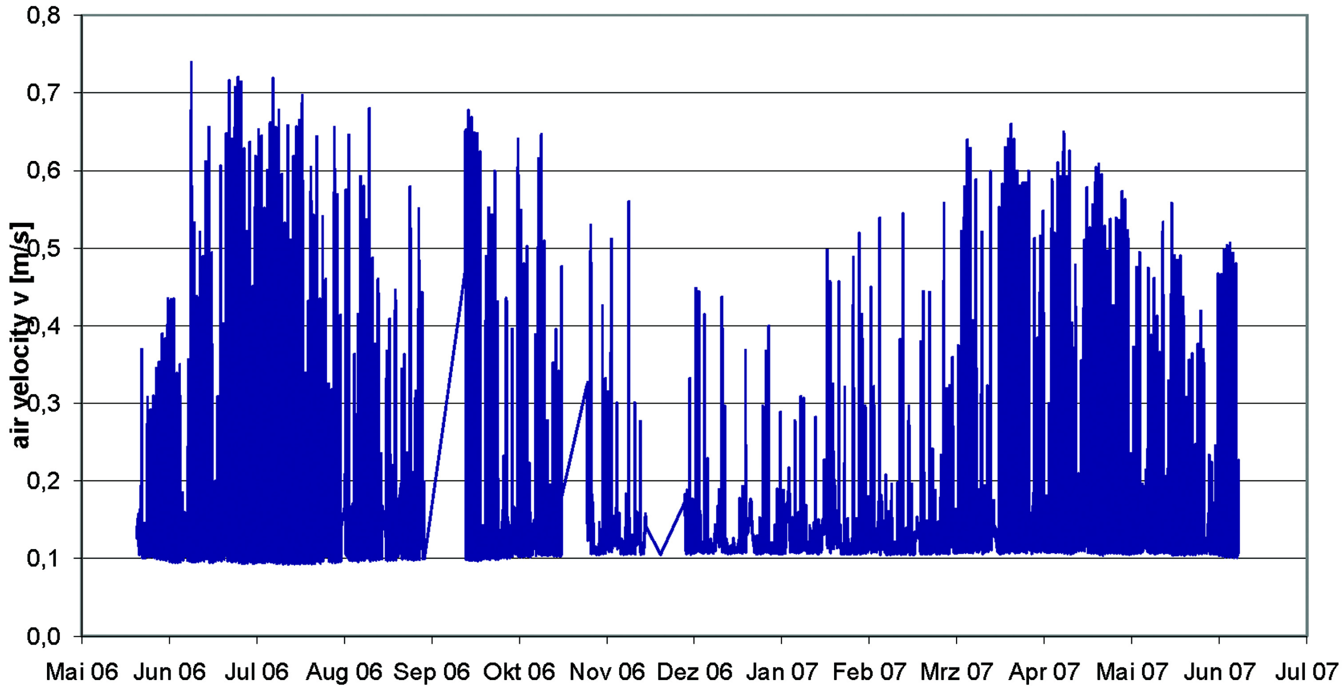
For the main question of whether condensate will form or fall on the paint and cause damage, the dew-point temperature θ_{DP} was calculated from air temperature θ and relative humidity Φ, and was compared with the surface temperature θ_s. If $\theta_s < \theta_{DP}$, condensate may form on the surface. This risk is shown in Table 3 for the five relevant days and for both windows.

ANALYSIS

A comparison of the time variation curves and some correlation calculation shows the following interdependences.

Temperatures and Buoyancy

Because of the air gaps at the top and bottom of the clearance, the connection to the internal air of the church, and the temperature differences within the clearance as well as to interior of the church, there is convection that brings new air from the church into the clearance. This convection depends very much on solar radiation (as shown in Figures 8 and 10), which is much stronger on the southern side than on the northern. In this case, air flows upwards. On cloudy, cold days and on cool nights, the cooler external air causes an airstream down. Because of these airflows (either up or down), the temperature of the inner painted glazing adapts to that in the church, and the risk of condensation is reduced. Table 4 shows a qualitative overview of the results comparing the northern and southern window as interactions of



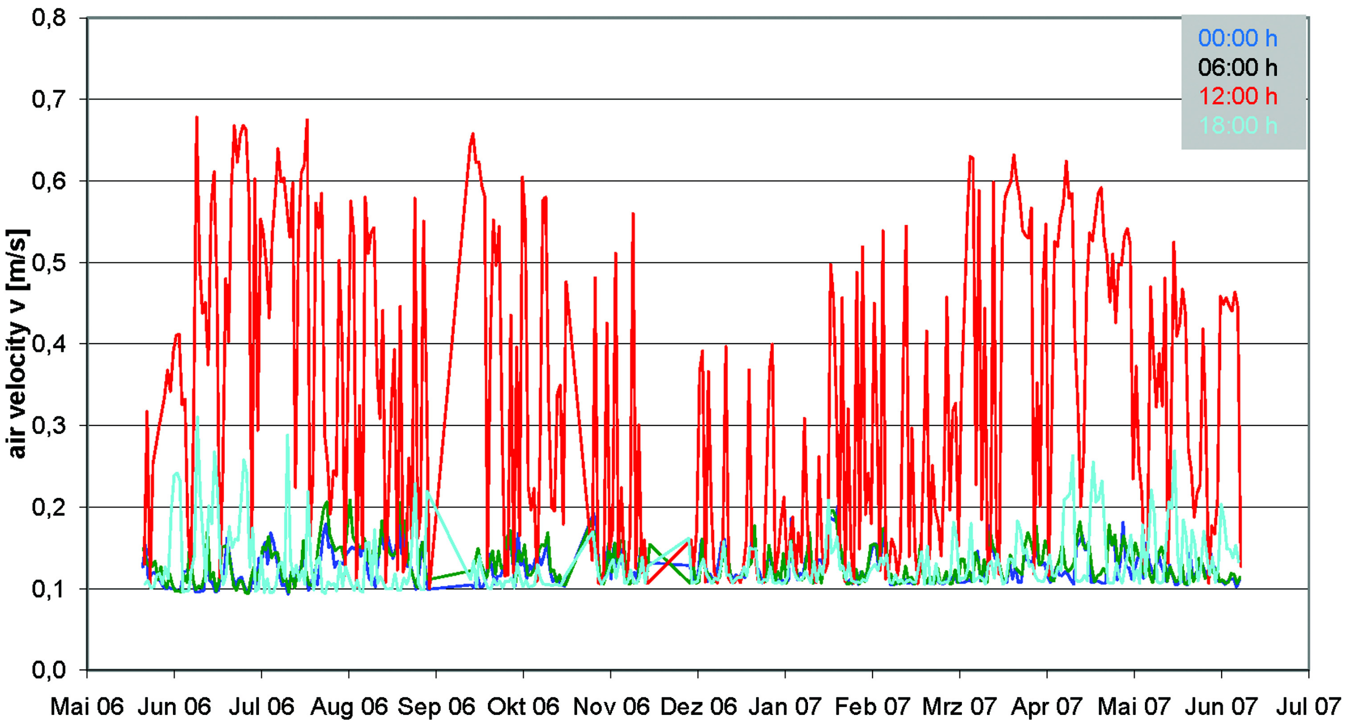


Figure 8 *Time variation curve for air speed within southern clearance for 1 year. Top: ordinary graph of hourly data. Bottom: graphs for speeds at 0 h, 6 h, 12 h, and 18 h.*

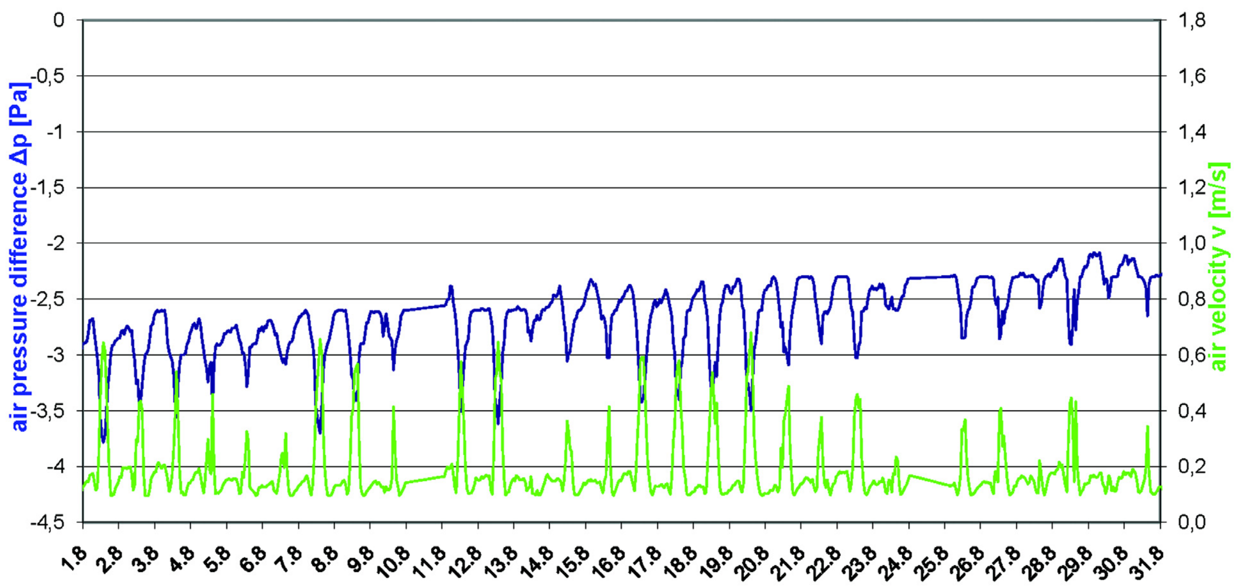


Figure 9 *Time variation curves for air speed and air pressure within southern clearance for one month: August 2006.*

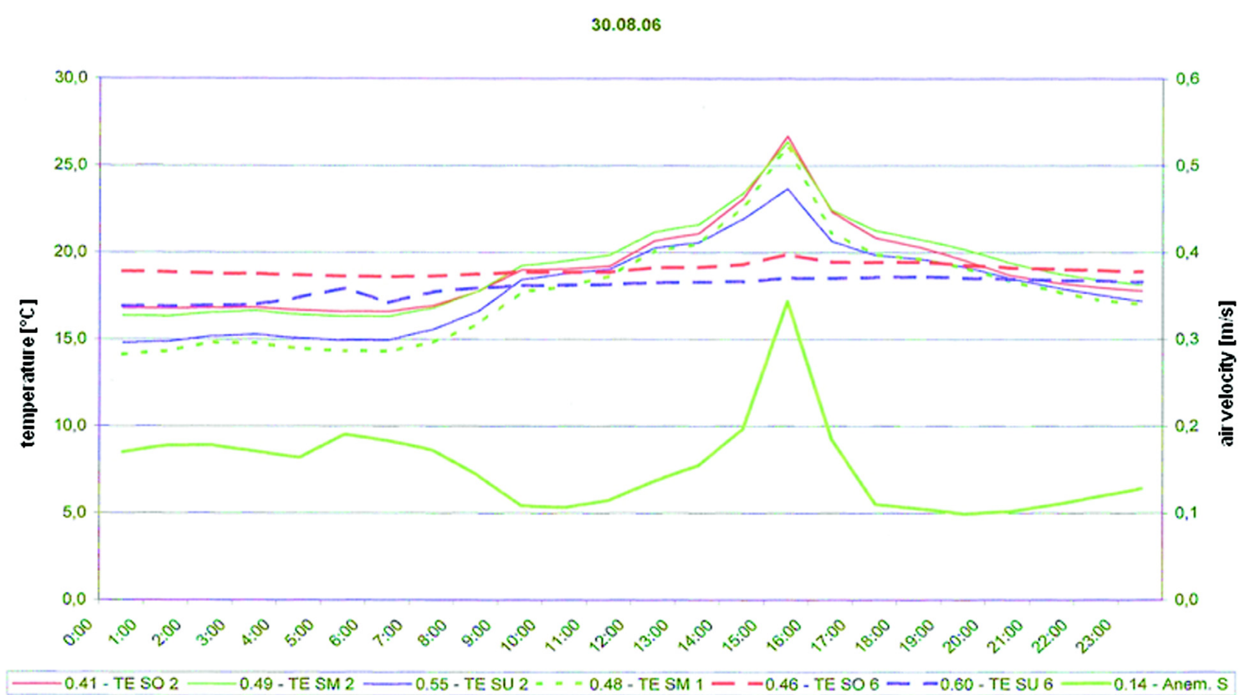


Figure 10 *Time variation curves for air speed within southern clearance (green) and temperatures for one day: August 30, 2006.Code for lines: red = top; blue = bottom; continuous: outside; dashed: inside; dotted: clearance.*

Table 2. Criteria to Chose Days for More Detailed Analysis

Day	Season	Cloudiness	Direct Solar Radiation	Other
		Parameters		
2006-08-03	Summer	Low	High	High temperature in clearance space
2006-08-30		High	Low	Low temperature in clearance space
2007-01-26	Winter	High	Low	Day follows directly before mentioned
2007-01-27		Low	High	
2007-02-26		High	Low	

Table 3. Condensation Risk at Window Surfaces for Different Times of the Day

Choir Window	Surface	Season / Date / Solar Radiation: Summer 2006-08-03 High	Summer 2006-08-30 Low	Winter 2007-01-26 Low	Winter 2007-01-27 High	Winter 2007-02-26 Low
North	Protecting glazing outside	—	—	—	—	Morning
	Protecting glazing inside	Morning	Morning	Morning Noon	Whole day	Whole day
	Interior glazing outside	—	Morning Night	—	Morning Evening	Whole day
	Interior glazing painted inside	—	—	—	—	—
South	Protecting glazing outside	—	—	n.s. *	n.s. *	Morning
	Protecting glazing inside	Morning	Morning	n.s. *	n.s. *	Morning Night
	Interior glazing outside	—	Morning	—	—	Morning Night
	Interior glazing painted inside	—	—	—	—	Night

*n.s. = no signal. Probably the lead of the window and the copper of the sensors formed a galvanic element under condensation and produced illogical values

- Air temperatures between exterior and clearance. "Partly" means synchronous for some hours, disturbed by radiation.
- Temperatures in the clearance at three different heights to interpret the impetus for buoyancy
- Interior temperatures at the bottom and top of the window
- Valuation of buoyancy compared to temperature differences in the clearance (see Figure 10).

Air Pressure Differences

Air pressure differences from inside to outside were recorded, either over- or low-pressure, depending on the direction of the wind; values were much higher than those between inside and clearance. This shows that the new protective glazing is tight in the joints between the tiny glass tiles as well as in the joint to the wall, a result already attained from the short-time modified blower door test.

Correlation calculations show that the air speed in the clearance is very well suited to pressure difference between clearance and inside, but not with that to the outside.

Humidity at and beside Window

Condensation on glazings may occur when the measured surface temperature is lower than the dew-point temperature of the air, which can be calculated from the air temperature and relative humidity. For the different surfaces of both windows, the time condensation risk is plotted in Figure 11. Figure 12 shows the location of measurement and the code for Figure 11.

On the north side, very short times of condensation could be registered on the inner painted surface of the inner glazing (squares 11 and 12), while on the south window condensation occurs in wintertime. Table 3 shows that this may happen on

Table 4. Interactions between Temperatures θ and Buoyancy for Different Times of the Day

Choir Window	Surface	Season / Date / Solar Radiation	Summer 2006-08-03 high	2006-08-30 low	Winter 2007-01-26 low	2007-01-27 high	2007-02-26 low
North	a) θ exterior vs. θ clearance		Nearly synchronous	Nearly synchronous	Nonsynchro-nous	Nonsynchro-nous	Nearly synchronous
	b) θ clearance **T**op vs. **M**id vs. **B**ottom			10-14: **M>T,B** 18-22: **M>T,B**		14-17: **T=M**	as 2006-08-03
	c) θ interior **t**op vs. **b**ottom			day: **T>B** (layering). night: **T<B** (convection, radiation)		00-24: **T>B**	as 2006-08-03
	d) buoyancy vs. Δ θ **clearance** **				night: + day: **(+)**		
South	a) θ exterior vs. θ clearance		n.s. *	n.s. *	partly synchro-nous	non synchro-nous	partly synchro-nous
	b) θ clearance **T**op vs. **M**id vs. **B**ottom		00-17: **M,B<T** 17-19: **M,B>T** 19-24: **M>B,T**	22-05: **T>M,B** 05-22: **M>T,B**	10-24: **M>T,B**	08-15: **T>M,B** 15-24: **M>T,B**	00-24: **M>T,B**
	c) θ interior **t**op vs. **b**ottom			day: **T>B** (layering). night: **T<B** (convection, radiation)		day: **T>B**	night: **T>B**
	d) buoyancy vs. Δ θ clearance **		day: ++	day: ++	—	day: ++	day: +

* n.s. = no signal. Because of illogical values, no interpretation is possible.
** This line describes the dependence of buoyancy in the clearance on its temperature differences: no interaction.
(+) small; + good; ++ very good.

cloudy winter nights (2007-02-26), but not always (2007-01-26). A brief condensation less than three days, especially in winter, is not relevant for the growth of microorganisms.

Water on the lead tray at the bottom of the window was detected rarely in winter time, which might be condensed water on the glazing or wind-driven rain pressed through the joints of the glass tiles that then ran down.

The moisture content of the brickwork at the sides of the windows varied from 1.5% in winter to 0.5% in summer, which means that it is nearly dry.

Comparison North–South

Comparing the data and graphs from the northern and southern windows, we can see that the effect of solar radiation is good for the temperatures, buoyancy within the clearance, and, therefore, the reduction of condensation risk. Nevertheless, the northern window also shows acceptable results.

Microorganisms on Paint

The examination of one painted surface by Dr. Messal before (Micor 2006) and after (Micor 2007) measurement show that different microorganisms settled on the painting, but they were no longer alive.

APPRAISAL

The questions from the introduction can be answered as following:

The exterior protection glazing is tight in the joints between the glass tiles and in those to the wall. Water will not penetrate the joints, except perhaps under worst-case conditions (e.g., a storm in winter time), but this short-time occurrence is nonhazardous with regard to microorganism growth.

Ventilation of the clearance to the inside (not to the outside, as is usual in ventilated constructions) is necessary and prevents an increase of humidity and condensation.

The influence of the walls regarding humidity in the clearance is negligible, because the walls can be considered to be nearly dry.

The risk of condensed water on the painted surface of the interior glazing was only for a relatively short time. It did not lead to a any long-term vital population of microorganisms.

CONCLUSIONS

The research demonstrated that the chosen construction worked well. Therefore, the following rules are recommended:

The new exterior protective glazing has to be as tight as possible. Modern sealing material can ensure this, but it is not recommended for the restoration of heritage buildings. This

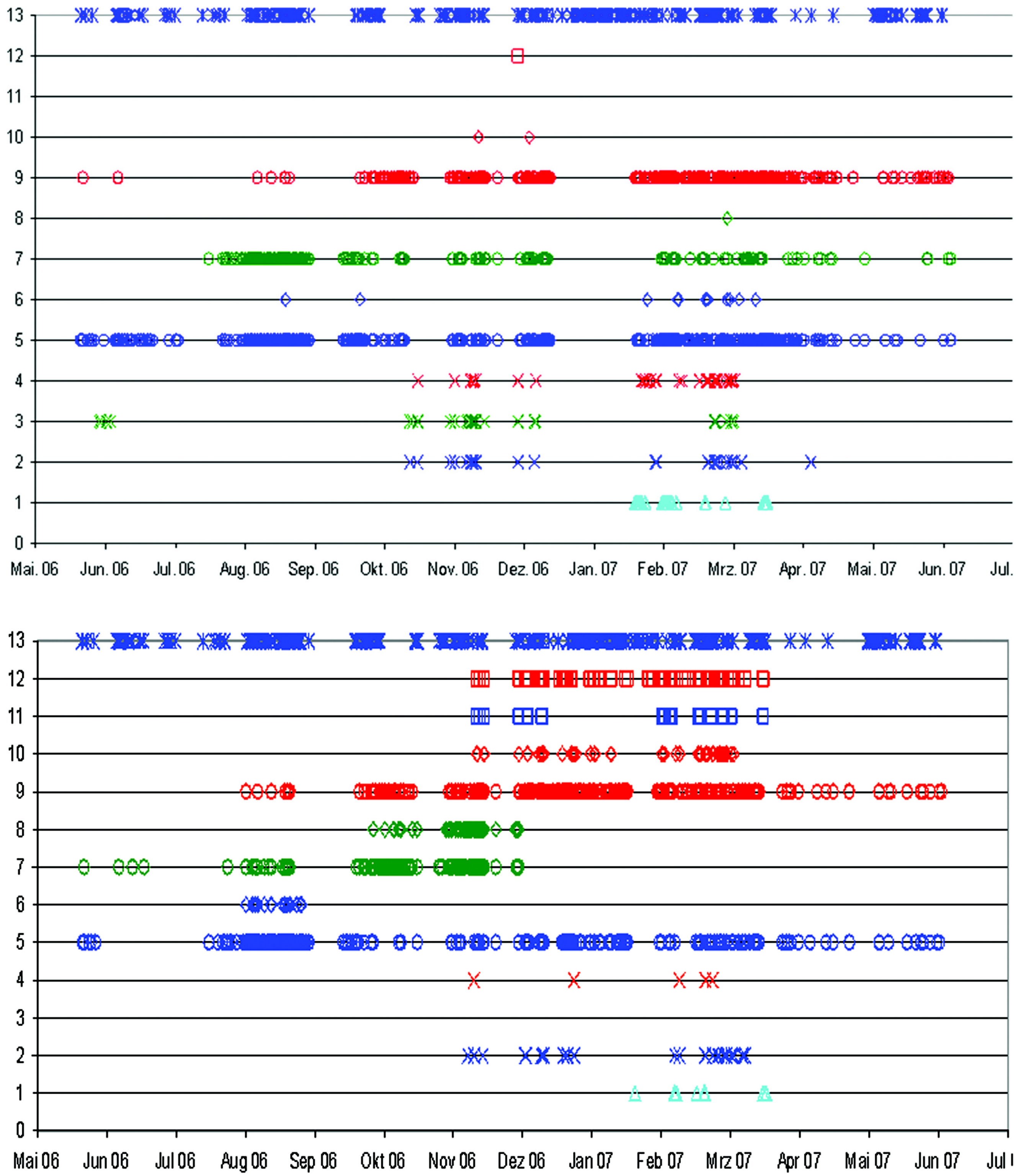


Figure 11 *Appearance of water at the windows for one year. Top: southern window; bottom: northern window.*

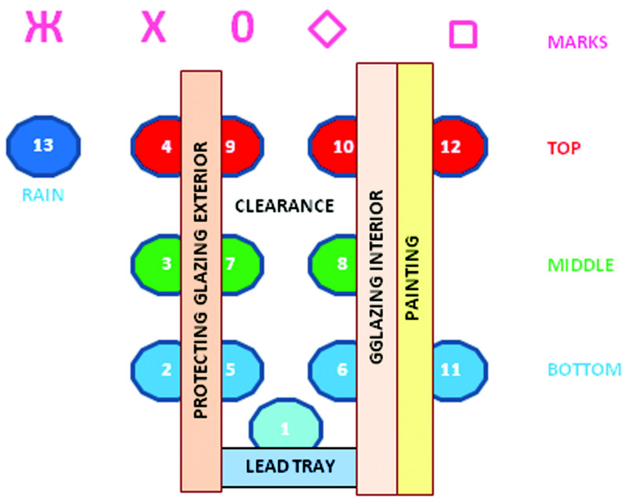


Figure 12 *Allocation of rows in Figure 11 to places on the glazings.*

means that good workmanship is needed for the joints between the glass tiles and for those between the side walls and the windows. The newly developed joint to the wall in traditional manner (hemp rope, mortar, lead flashing) is tight and seems to be long lasting.

The space between glass should be a minimum of 40 mm (1.5 in.). In no case should it be reduced, for example by a horizontal obstacle within the clearance.

The space between the glazings has to be ventilated to the inside, not to the outside as usual.

By inclining the upper and lower glass plate with a gap of 25 mm (1 in.), convection by buoyancy within the clearance will be guaranteed.

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