CANVAS PAINTINGS ON COLD WALLS: RELATIVE HUMIDITY DIFFERENCES NEAR THE STRETCHER.

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ABSTRACT

A frequently observed phenomenon with canvas paintings is the sharp transition in the condition of canvas and paint layers in the regions directly adjacent to the stretcher, strainer or cross bars and the condition of the painting in the other regions, behind which no wood is present. This paper explores the idea that this transition, referred to as the ‘stretcher effect’, is the result of a local *deviation of the relative humidity* in the vicinity of the stretcher. Two plausible mechanisms, thermal shielding and hygroscopic buffering are investigated both theoretically and experimentally. It was found that thermal gradients cause significant variations in relative humidity near the canvas and thus play a major role in the formation of the stretcher effect.

1 INTRODUCTION

Degradation processes in art objects are usually slow and gradual. Although this situation is preferable from a curator’s point of view, it presents a problem for conservation scientists who would like to clarify the mechanisms responsible for these degradation processes. In the absence of direct information on the behaviour over time, local spatial differences in the condition of a material within a single object can provide important clues to factors that enhance or reduce degradation. These local differences are therefore of special interest to conservation science.

In the field of the conservation of canvas paintings an example of such a local difference is the variation between the condition of the paint layer and of the canvas in the regions directly over the stretcher, strainer or cross bars and the condition of the painting in the other regions behind which no wood is present. From here on we will use the generic term ‘stretcher’ to indicate any part of the wooden support of the canvas, and refer to the local, sharp transition in the condition of the painted canvas as the ‘stretcher effect’. A detail of a painting exhibiting this phenomenon is shown in Figure 1.

Although the ‘stretcher effect’ is well known to paintings conservators [1], no systematic survey has been published to describe the pervasiveness and the common characteristics and variations of the phenomenon. We believe that such a survey is needed. However in this paper we focus on elucidating the mechanism of its formation.

Various ideas have been proposed to explain the stretcher effect. Those ideas need to explain the sharp transition of the condition of the canvas at the stretcher’s edge. One possible mechanism for the occurrence is a direct *mechanical contact* between stretcher and canvas. In many paintings the stretcher is in close contact with the canvas and it provides direct mechanical support to the canvas. Mechanical vibrations are attenuated where the stretcher is present, but not outside the stretcher region. This attenuation can lead to a locally different condition of the canvas [2]. A second possible mechanism that might lead to the stretcher effect is a *locally modified chemistry* caused by the transfer of volatile components between stretcher and canvas. Although the transfer of volatiles might in principle lead to local variations in the mechanical properties of the canvas and paint layers, no direct experimental evidence is available to support this idea.

The third and probably most popular explanation for the effect is the idea that the presence of the stretcher induces a local *deviation of the relative humidity* behind the canvas which controls the moisture content of the canvas, ground, and paint layers. This local deviation of the moisture content will lead to a locally distinct swelling of the layers in the painting at the stretcher area in comparison to the area where no stretcher is present. Over time this might lead to the ‘stretcher effect’. While differences in the moisture content of the canvas are very difficult to measure directly, the relative humidity of the air in close proximity to the canvas, being an indicator of its moisture content, is easy to measure. A few studies have been published on micro-climate and local variations of relative humidity and temperature in paintings and comparable semi-closed environments [3, 4, 5, 6]. In this study we investigate the mechanisms responsible for the occurrence of local relative humidity differences near the canvas. Our curiosity to understand the stretcher effect is related to the use of backing boards in paintings conservation.

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Figure 1. An example of the stretcher effect: the condition of the painting is better in the area over the stretcher. Detail (0.3 x 0.3 m) of The Coronation of Maria, Church of the Heilige Bavo at Nuth, Netherlands. Photo courtesy Stichting Restauratie Atelier Limburg (SRAL)

2 THEORY OF THE LOCAL STRETCHER CLIMATE

We can think of two distinct properties of the stretcher that are candidates to play a significant role in the formation of a local stretcher climate. Stretchers are made of wood which is both hygroscopic as well as thermally insulating. In the following we will explore two distinct mechanisms through which both properties will affect the local stretcher climate.

HYGROSCOPICALLY INDUCED RELATIVE HUMIDITY DIFFERENCE

In Figure 2, a cross section view of a typical painting geometry with a stretcher adjacent to a canvas plus a wall is shown. Consider a situation in which the overall temperature is maintained constant. Suppose now that all the hygroscopic materials in this painting initially are in equilibrium with a constant relative humidity. In the next stage of this conjectured experiment the relative humidity in the room is changed to a new, let's say lower, level. In reaction to this change, both the stretcher and the canvas will release moisture to the surrounding air. For some time, the moisture content of the canvas in the stretcher area and the relative humidity in the air pocket between stretcher and canvas will remain close to the original level and resist following the general change of relative humidity. The magnitude and duration of the relative humidity difference, and the shape of the relative humidity profile in the stretcher area will depend on the rate of supply of moisture from canvas and wood in competition with the transport of moisture in the narrow air gap between canvas and stretcher and the loss of water vapour by permeation through the canvas.

In our early work we were inclined to believe that this hygroscopic action of the stretcher would provide a satisfactory explanation for the stretcher effect. However, after performing some calculations for typical dimensions and material characteristics based on earlier studies [7, 8] (see appendix A), we became less convinced.

In the case of paintings well attached against the wall, where the decline of the RH at the back of the canvas takes of the order of hundreds of hours, the model predicts smooth profiles whose level slowly decreases in time (Figure 3a). In this case the permeation through the canvas dominates over the diffusional lateral flow. For smaller values of the canvas water vapour permeability the profiles are reversed but have the same smooth shape.

In the case of paintings hanging at a certain distance from the wall, the decline of the RH on the back of the canvas is of the order of few hours. The model predicts larger differences of relative humidity (Figure 3b). Apart from the first few hours, the shape of the profile is still gradual. This characteristic does not change by reducing the value of the canvas permeability or the distance between the stretcher and the canvas.

We believe that these smooth or short-lived profiles can not explain the sharp transition in the condition of the canvas typical of the stretcher effect.

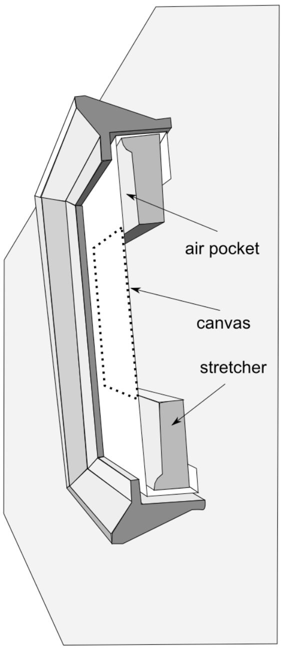


Figure 2. Cross section of a typical painting geometry.

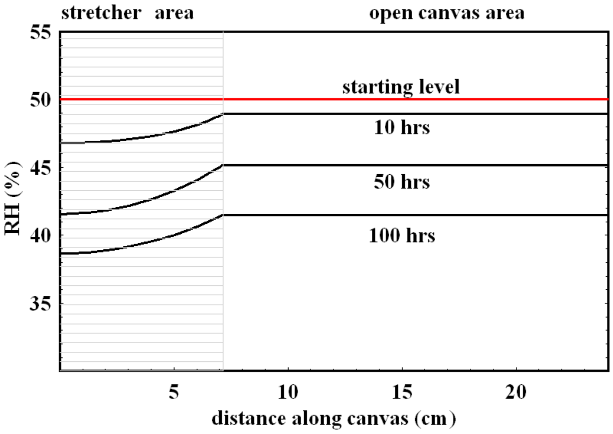


Figure 3a. RH profiles induced by the pure hygroscopic effect. The painting is close fitting against the wall.

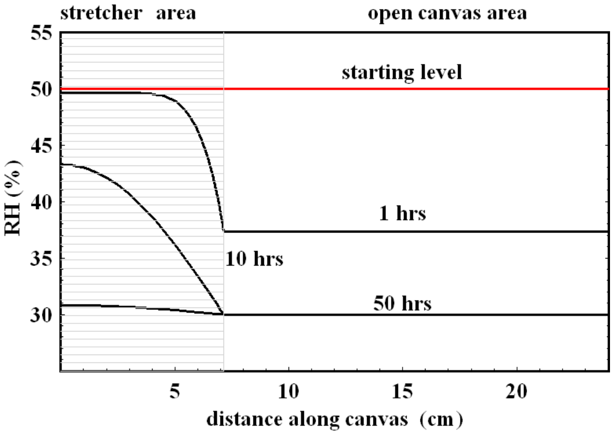


Figure 3b. RH profiles induced by the pure hygroscopic effect. The painting is hanging away from the wall.

Thermally induced relative humidity difference

This inconsistency made us look for an alternative mechanism that would give rise to a more pronounced local stretcher climate with a sharper transition. The starting point for the development of an alternative mechanism was an early thermograph picture by Urbani [9] of a canvas painting mounted on a wall. The picture clearly shows the pattern of the stretcher and crossbars underneath the painting, indicating a temperature difference. This specific example may represent a general effect that will occur for paintings that are subjected to a temperature difference between room and wall. The stretcher present between canvas and wall will locally block radiative and convective heat transfer between wall and canvas and thus should cause a temperature variation along the canvas with a relatively sharp transition at the stretcher edge. As a consequence, this temperature difference would induce local relative humidity differences.

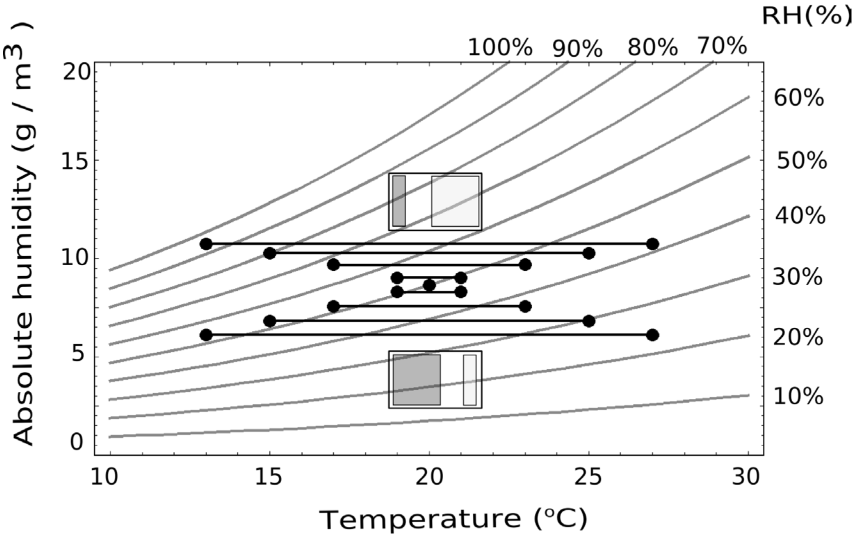
A quantitative prediction of local relative humidity resulting from spatial temperature differences in a system with hygroscopic materials and air is difficult for a general case. The major difficulty is the complex moisture diffusion behaviour in hygroscopic materials subjected to thermal gradients [10]. However for cases that can be modelled as systems with a number of hygroscopic surfaces at different but individually uniform temperatures, all in contact with a common air volume, the situation is simpler [11].

In most systems subjected to temperature variations, significant convective flow of air will be generated. As a result there will be a constant mixing of air. This mixing will cause the water vapour concentration (absolute humidity) within the air volume to equalize throughout the open space bounded by the different hygroscopic materials. Near surfaces, the temperature of the air will conform to the local surface temperature. The combination of a local surface temperature and a global absolute humidity gives rise to a different relative humidity at each surface. As soon as all local surface relative humidities are in equilibrium with the local moisture contents of the materials, the global absolute humidity will remain constant.

In this study we developed a two-step model to predict the local equilibrium relative humidity values that would result from a given temperature distribution. The starting point is a uniform temperature and RH, with all materials equilibrated to these conditions. A temperature difference is now applied between the wall surface and the room air. The calculation in the model proceeds in two steps. In the first step the new global absolute humidity level that will develop as a result of different contributions of different parts of the system is calculated. Once this global value of absolute humidity has been determined, the local relative humidity can be calculated, everywhere in the system, just depending on the local temperature. This second operation is equivalent to reading relative humidity values from a hygrometric chart at a single absolute humidity level for different local temperatures.

The two-step model (for a full mathematical description see Appendix B) essentially predicts to what extent moisture will migrate from warm to cold material sections of the painting and how final relative humidities will depend on the relative masses of the material sections. If the masses of the materials in the cold sections exceed the masses of the materials in the warm sections there will be an overall decrease of the relative humidities. In the opposite case there will be an overall increase of the relative humidities and condensation can take place at the cold sides. Box

Box A simple system with hot and cold masses



To illustrate the model of equation 8 (appendix B), we consider here a simplified situation of an inert, moisture impermeable box containing two separate sections of hygroscopic material with different masses in a ratio of 4:1.

Starting from a uniform distribution of both temperature and relative humidity at 20 °C and 50%, we will consider the effect of cooling one section of hygroscopic material in the box to a temperature of 13°C while heating the other section to 27°C in equal steps simultaneously. For two distinct cases, the local temperatures and the resulting humidity conditions are plotted in the hygrometric chart above:

1. *Major mass heated and minor mass cooled*

Due to the fact that the major mass is heated its moisture release will dominate the process. The global absolute humidity level will increase from its starting level of 8.7 g/m^3 to a level of 10.7 g/m^3 resulting in two separate relative humidity values at 95% and 42% respectively. It should be noted that the relative humidity at the cold mass is approaching condensation conditions.

2. *Major mass cooled and minor mass heated*

Due to the fact that the major mass is cooled its moisture uptake will dominate the process. The global absolute humidity level will decrease from it's starting level of 8.7 g/m^3 to a level of 6.1 g/m^3 , resulting in two separate relative humidity values at 54% and 24% respectively. It should be noted that the relative humidity at the warm mass is approaching comparatively dry conditions.

The major point to note in this simple example is that the mass distribution in a system exposed to a temperature gradient plays an essential role in determining the resulting relative humidity conditions.

1 shows the results of this calculation for a simple system.

3 Experimental set-up and procedure

In order to test our hypothesis that local differences in moisture content of the canvas and paint layers are mainly determined by spatial temperature gradients we developed experiments in which a canvas painting could be exposed to both temperature and relative humidity gradients.

Our experimental set-up consisted of a mock-up painting set against a wall which could be cooled, inside a walk-in climate room. We designed the painting so that it would have the typical moisture and heat transfer of a painting hanging closely against a wall but be simple enough to be understood with relatively simple math. We first describe the climate room, then the wall and finally the painting. Details about the materials and instruments will be given at the end of the paragraph.

The climate walk-in room has relative humidity and temperature controlled by a standard air-conditioning system. Both the temperature and the relative humidity can be changed within a few minutes. A relative humidity gradient across the painting is established by suddenly changing the RH in the room. Due to the low permeability of the

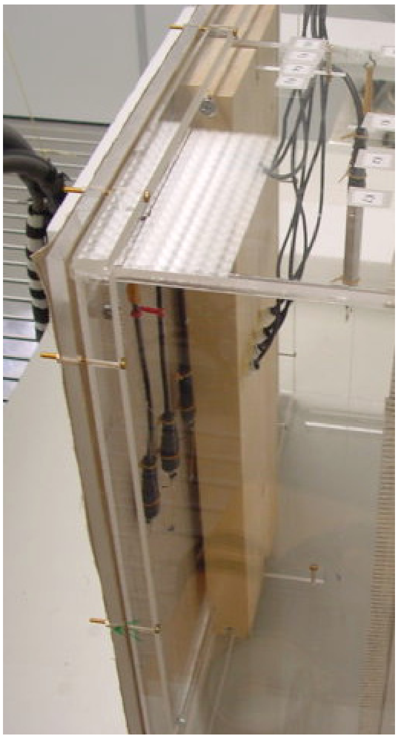


Figure 4. Side view of the mock-up painting with insulation material removed. It shows the acrylic frame, the canvas and the array of sensors positioned along the stretcher bar.

canvas, it will take a certain time for the relative humidity behind the painting to reach equilibrium with the room.

The wall is a gypsum wall containing internal water pipes connected to a thermostat. The wall was covered with a plastic foil and a cardboard sheet to give it well defined hygroscopic behaviour.

The painting is a canvas attached to an acrylic frame hanging on the wall.

The air conditioning system in the climate room produces strong air currents which can push air behind the painting, so we closed the gap between painting and wall and we thermally insulated the sides of the painting. To imitate a stretcher, we placed a wooden bar behind the centre line of the canvas.

In order to study the effects of individual hygroscopic surfaces, as predicted by the two-step model, we designed the experiment so that the hygroscopicity of the wall and of the wooden bar could be varied. When we wanted to imitate a system with a suppressed hygroscopicity, the stretcher was covered with a plastic foil and the cardboard was removed from the wall.

We measured the surface temperatures of the wall and of the two faces of the wooden bar with sensors glued to the surfaces. The temperature profile on the canvas surface was measured by bending the temperature heads of six RH&T sensors. The relative humidity and temperature of the air close to the wall was measured by a single RH&T sensor. The relative humidity of the air close to the canvas was measured with the RH heads of the previously mentioned six sensors. Three sensors were placed in slanting holes in the bar with their heads sticking out of the stretcher. Another three sensors were attached to nylon threads stretched from the bottom to the top of the frame (Figure 4).

The system is an enclosed volume with a number of surfaces: the canvas, the stretcher and the wall (Figure 5) Nine different hygroscopic surface units are distinguished: the wall, the two stretcher surfaces and six strips of canvas. The relative humidity is measured in seven locations: in the open space between wall and stretcher and in the six locations along the canvas. At these RH-sensors we did not measure the temperatures separately and therefore we had to estimate them. The temperature at the RH-sensors measuring in the air pocket between canvas and stretcher was taken as the interpolation between the measured temperatures at the canvas and at the stretcher surface. The temperature of the RH-sensors in the open canvas area was taken as the average between the canvas surface temperature and the temperature of the air region near the wall.

Experiments

The first experiment was designed to investigate hygroscopically induced humidity differences. A relative humidity gradient across the painting was induced by suddenly changing the relative humidity

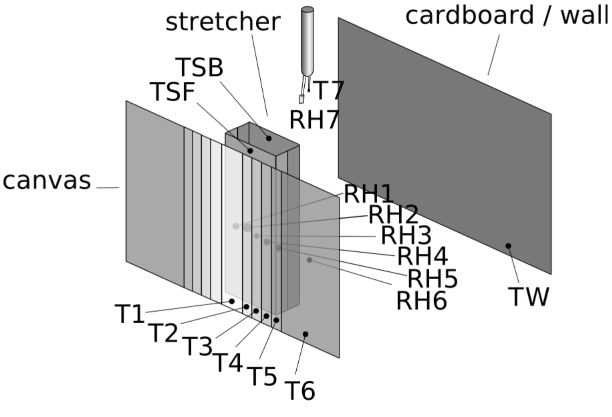


Figure 5. Diagrammatic sketch of the hygroscopic surface units present in the painting with indication of temperature and relative humidity sensor positions.

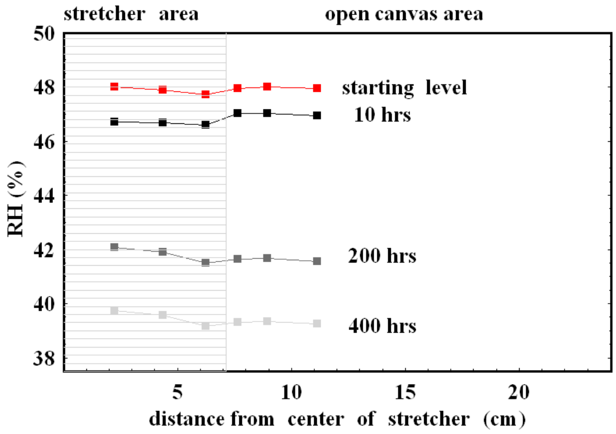


Figure 6. Relative humidity profiles along the canvas measured in the first experiment after 0, 10, 200 and 400 hours after the sudden decrease of relative humidity in the room. The striped area is the region occupied by the stretcher .

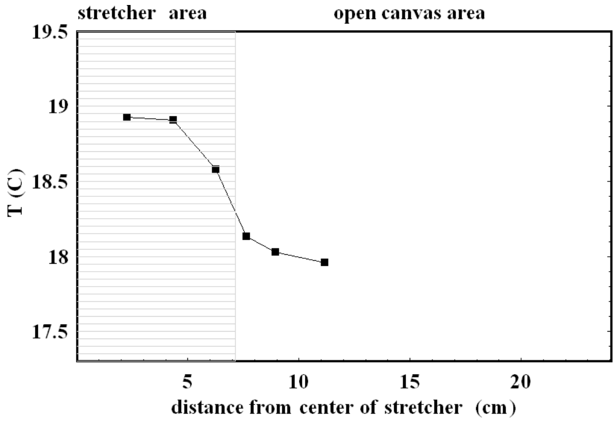


Figure 7. Temperature profile along the canvas in the second experiment. The striped area is the region occupied by the stretcher.

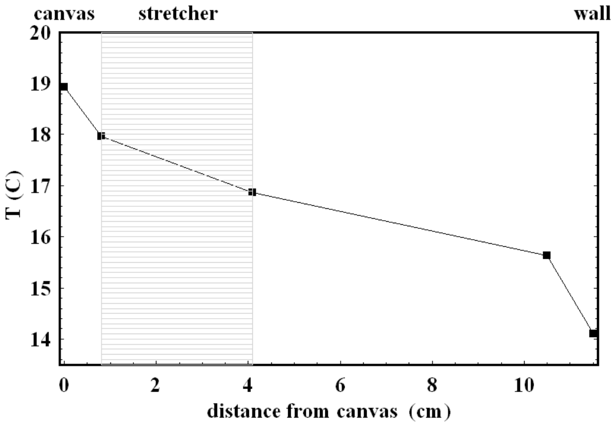


Figure 8. The temperature profile in the direction perpendicular to the canvas in the second experiment. The lines are to guide the eye. The striped area is the region occupied by the stretcher.

in the room from 50 % to 30 %, while keeping the temperature constant at 20 °C.

The second and third experiments were designed to investigate thermally induced relative humidity differences. A thermal gradient was created by keeping the relative humidity and the temperature in the room constant at 50% and 20 °C and decreasing the temperature of the wall to 14 °C. In the second experiment the hygroscopicity of the wall and stretcher were suppressed by temporarily removing the cardboard from the wall and covering the stretcher with a plastic foil. In the third experiment the hygroscopic action of stretcher and cardboard was restored.

Details of the materials and instruments used and on the RH and T values.

The painting has an oil-primed canvas of dimension 48.5 ×48.5 cm glued to a polymethyl methacrylate **(**PMMA**)** frame designed to keep the canvas at 11.5 cm from the wall. The space between the frame and the wall is closed with PMMA strips screwed to the frame. The edges of this construction are sealed with waterproof tape and insulated with polystyrene foam board to prevent moisture and heat exchange through the sides of the assembly. The stretcher is a pine wood bar of 48 × 14.3 × 3.3 cm. It is placed 0.8 cm from the canvas. The cardboard used to cover the wall area is an alkaline Moorman cardboard with density of 1200 g.m^{-2}.

The RH&T sensors are capacitance and NTC thermistor sensors produced by Hygrotech, Germany (Semi 833 NTC and Humicor 5000). The relative humidity heads are positioned at approximately 0.5 cm distance from the canvas. The temperature of the wooden bar and of the wall was monitored with thermocouples. The temperature and relative humidity in the room was monitored with two Vaisala HMM 30D sensors.

4 Results and discussion

Figure 6 shows the relative humidity profile along the canvas measured in the first experiment where the system was subjected to a relative humidity change and the temperature was kept constant and homogeneous. The profiles at 0, 10, 200 and 400 hours after the sudden decrease of relative humidity in the room from 50% to 30% are shown in the graph. The RH profile shifts downwards with time, due to the leakage of moisture from the system to the room through the canvas. The slow approach to 30% RH is caused by buffering by the wood and cardboard.

In disagreement with our diffusion models, the observed RH profiles are flat within the experimental error. Hence, exposure to pure relative

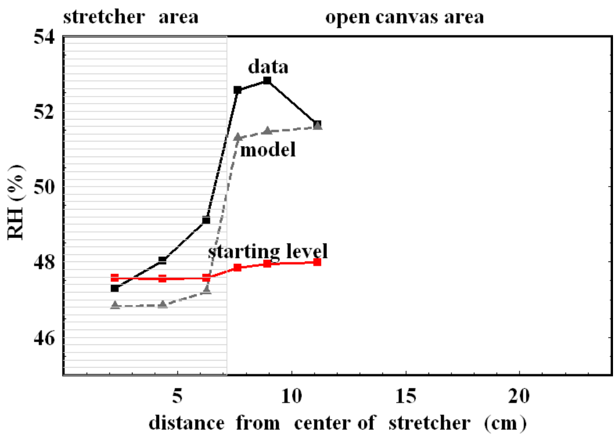


Figure 9. Measured and calculated relative humidity profile along the canvas in the second experiment (stretcher and wall buffering suppressed).

humidity gradients across canvas paintings does not induce significant relative humidity profiles. This means that the moisture content of the canvas also does not change significantly along the canvas and therefore that, under typical values of distance between stretcher and canvas like the one used in the experiments, pure relative humidity gradients cannot induce the stretcher effect.

Figures 7 to 10 show the results of the second and third experiment, where the system was subjected to a gradient in temperature. After starting the cooling procedure it takes 6 hours to reach a steady temperature gradient between room and wall. Figure 7 shows the temperature profile in the plane of the canvas. Figure 8 shows the temperature profile perpendicular to the canvas. The temperature difference between the centre of the stretcher and the centre of the free canvas is one degree. The perpendicular temperature profile shows that the temperature of the canvas is close to the room temperature, 20 °C. Very similar temperature profiles were observed in the third experiment.

Figure 9 shows both the measured relative humidity profile along the canvas in the second experiment once the temperature profile had reached stability, and the predicted profile calculated by applying equation B8 (appendix B). The parameters needed to calculate the profile are listed in Table 1a. The profile is very steep at the stretcher edges. The total relative humidity difference is about 5%. The model is in good agreement with the experimental results.

Figure 10 shows three measured relative humidity profiles along the canvas in the third experiment (with buffering by wall, stretcher and canvas) at 0, 6, 200 and 500 hrs after applying the thermal gradient, and the predicted profile after 6 hrs. The parameters needed to calculate the profile are listed in Table 1b. The relative humidity profile is steep at the stretcher edges and it levels out at the centre of the stretcher and in the region of the canvas not covered by the stretcher. The shape of the profile is constant but moves to a higher RH with time. The relative humidity started at 47%. After 6 hours from applying the thermal gradient the relative humidity between canvas and stretcher had dropped to about 40% due to the absorption of moisture by the materials whose temperature was decreased. This relatively large reduction in RH is primarily caused by the substantial cooling of the cardboard against the wall. Afterwards the level of relative humidity increased due to equilibration with the water vapour content of the room, into the system through the canvas. The model matches well the experimental results.

5 CONCLUSIONS

The measured and predicted magnitude and steepness of relative humidity profiles along the stretcher indicate that the stretcher effect found in canvas paintings is most likely due to temperature induced relative humidity gradients in the plane of the canvas. The direct local hygroscopic action of the stretcher wood is negligible. Our experimental results are in good agreement with the proposed model for thermally induced relative humidity differences. The model shows that the moisture distribution in objects like paintings depends strongly on the presence of temperature gradients and on the distribution of the dry masses within the object. Moisture will accumulate in cold hygroscopic materials and can practically only be controlled if temperature gradients are reduced.

This study provides a quantitative argument to confirm the idea of Padfield and co-workers (2001)

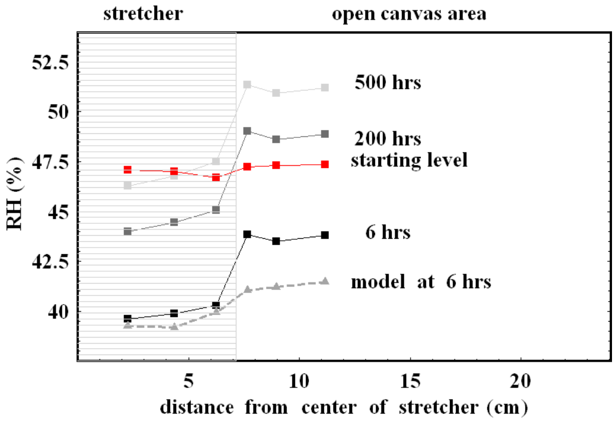


Figure 10. Relative humidity profile measured along the canvas in the third experiment (with buffering by absorbent wood and wall) after 0, 6, 200 and 500 hours from the setting up of the thermal gradient, and the calculated profile after 6 hours.

Initial Condition	Mass of Hygroscopic surf. (g) (*)	Temperature of surfaces (C)	New level of Abs. Humidity
RH = 48% T = 20 C AH =8.31 g/m^3	M1 = 11.88	TS1=18.9	AH=6.14 g/m^3
	M2 = 7.2	TS2=18.9	
	M3 = 6.66	TS3=18.6	
	M4 = 4.14	TS4=18.1	
	M5 = 6.3	TS5=18.0	
	M6 = 44.82	TS6=17.9	

⇒

Interpolated Air Temp. (C) (**)	Calculated Air Hum. (%)
TA1 = 18.3	RH1 = 46.8
TA2 = 18.3	RH2 = 46.8
TA3 = 18.2	RH3 = 47.2
TA4 = 16.9	RH4 = 51.3
TA5 = 16.8	RH5 = 51.4
TA6 = 16.8	RH6 = 51.6

Table 1a. Parameters and results for the humidity profile in the second experiment (see Figure 4 for the location of the surfaces and of the measuring points)

Initial Condition	Mass of Hygroscopic surf. (g) (*)	Temperature of surfaces (C) (***)	New level of Abs. Humidity
RH = 47% T = 20 C AH =8.13 g/m^3	M1 = 11.88	TS1 = 18.9	AH=5.44 g/m^3
	M2 = 7.2	TS2 = 19.0	
	M3 = 6.66	TS3 = 18.7	
	M4 = 4.14	TS4 = 18.2	
	M5 = 6.3	TS5 = 18.2	
	M6 = 44.82	TS6 = 18.1	
	MSF = 40.72	TSF = 18.1	
	MSB = 40.72	TSB = 17.0	
	MW= 282.27	TW = 13.6	

⇒

Interpolated Air Temp. (C) (**)	Calculated Air Hum. (%)
TA1 = 18.4	RH1 = 40.3
TA2 = 18.4	RH2 = 40.3
TA3 = 18.3	RH3 = 40.6
TA4 = 17.0	RH4 = 44.0
TA5 = 17.0	RH5 = 44.0
TA6 = 17.0	RH6 = 44.2

Table 1b. Parameters and results for the humidity profile in the third experiment (see Figure 4 for the location of the surfaces and of the measuring points)

(*) Mass of the canvas units: $M = s_w \times s_h \times \sigma$, where s_w is the strip width, s_h is the strip height (45 cm) and σ is the surface density of the canvas (0.04 g cm^{-2}). The strip widths are respectively 6.6 cm, 4 cm, 3.7 cm, 2.3 cm, 3.5 cm and 24.9 cm. , Mass of stretcher surfaces: $M = S \times \rho \times d$, where S is half of the total stretcher surface (792 cm^2), ρ is the wood density (0.6 g cm^{-3}) and d (0.086 cm) is the effective thickness of the wood, calculated as $d = (D \times t)^{1/2}$, with D the diffusion constant of moisture in wood ($3.4 \times 10^{-7} cm^2 s^{-1}$) [8] and t the time past since the beginning of the experiment (6×3600 s).

Mass of cardboard on wall: $M = c_w \times c_h \times \sigma$ where c_w is the cardboard width (48.5 cm), c_h is the cardboard height (48.5 cm) and σ is the surface density (0.12 g cm^{-2}).

(**) The temperature at points 1, 2 and 3 is interpolated based on a linear profile between the temperature of the canvas and the temperature of the front face of the stretcher. The temperature at points 4, 5 and 6 is the average between the temperature of the canvas and the temperature *T7* (15.6 C).

(***) In the third experiment the wall was covered by a cardboard sheet and the temperature of the wall was measured under the cardboard sheet. This underestimates the actual cardboard temperature which was therefore in the calculation assumed to be equal to *T7* (15.6 C).

who claim that when backboard protections are applied to drawings directly in thermal contact with cold walls, they may accumulate substantial amounts of moisture, which in changing temperature conditions can be released and result in dangerously high relative humidity values.

Although this study is aimed at the specific issue of the stretcher climate, we believe that the effects of temperature variation in semi-enclosed systems are of general importance in preventive conservation. The model we present is a powerful tool to predict and understand the distribution of the relative humidity in the general case of semi-closed systems subjected to temperature gradients.

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APPENDIX A. MODEL FOR HYGROSCOPICALLY INDUCED RH DIFFERENCE.

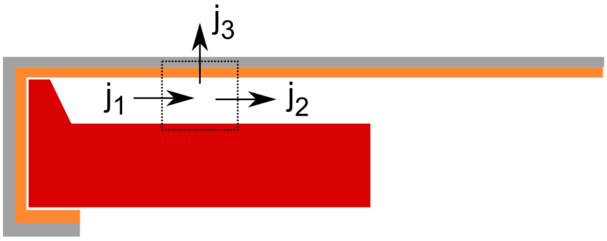

Figure A1. Sketch of the stretcher area with the permeation and diffusional flows determining the moisture transport in the air gap.

We want to calculate the profile of relative humidity building up along the stretcher pocket during the conjectured experiment explained in section 2. Neglecting possible convection of air, three main factors determine the relative humidity profile: the desorption (or absorption) of moisture by the stretcher and the canvas, the diffusion of moisture along the air pocket and the permeation of moisture through the canvas. We will assume that the desorption of moisture by the hygroscopic materials is so quick that the moisture content of the hygroscopic materials is always in equilibrium with the local relative humidity. This means that the contribution of the hygroscopic materials is taken into account by the (linear) relation between the equilibrium moisture content of the materials and the local relative humidity and by the prevailing amount of moisture contained in the hygroscopic materials with respect to air. The contributions of the diffusion of moisture along the air pocket and the permeation of moisture through the canvas are taken into account by assuming that the variation in time of the total moisture $m_V(x,t)$ [g] contained in the small representative volume V [cm^3] centered at position x [cm] is given by the balance between the incoming diffusional flow J_1 [g cm^{-2} s^{-1}] on one side and the outgoing diffusional flow J_2 [g cm^{-2} s^{-1}] and the permeation flow J_3 [g cm^{-2} s^{-1}] on the other side (see Figure A1).

The diffusional flows are given by Fick's law while the permeation flow is given by the relation:

$$J_3(x,t) = P \times (RH(x,t) - RH0) \qquad [A1]$$

where P [g cm^{-2} s^{-1}] is the experimentally determined permeability of the canvas [7, 8] and RH0 is the relative humidity level in the room.

Combining these ingredients, the differential equation which needs to be solved to find the relative humidity profile in the air pocket is:

$$\frac{d^2 RH(x,t)}{d^2 x}(x,t) + k_1 \times (RH0 - RH(x,t)) \qquad [A2]$$

$$= k_2 \times \frac{dRH(x,t)}{dt}$$

with:

$$k_1 = \frac{P}{d \times D \times c_{sat}}$$

$$[A3]$$

$$k_2 = \frac{\alpha \times \delta + \sigma}{d \times D \times c_{sat}}$$

where d [cm] is the distance between stretcher and canvas, D [cm^2 s^{-1}] is the diffusion constant of moisture in air, $c_{sat}(T)$ [g cm^{-3}] is the saturation moisture content in air at temperature T [K], α [dimensionless] is the constant of proportionality in the linear relation between the equilibrium moisture content of the materials and the local relative humidity, also called the hygroscopicity factor. δ [cm] is the thickness of the stretcher surface effectively desorbing moisture in the experimental time. ρ [g cm^{-3}] is the density of the wood and σ [g cm^{-2}] is the surface density of the canvas.

The boundary conditions to solve A2 are 1) that at the beginning the relative humidity is homogeneous in the air pocket, 2) that there is no flow of moisture at $x = 0$ (the pocket is closed on this side) and 3) that the relative humidity at the opposite side of the air pocket is known at each time and has a decreasing exponential behaviour [7].

For the numerical calculations of the profiles from figures 3a and 3b we have used the following values: $D = 0.25$ cm^2 s^{-1}, $c_{sat}(T) = 22 \times 10^{-6}$ g cm^{-3}, $\alpha = 0.15$, $\delta = 0.1$ cm, $\rho = 0.6$ g cm^{-3}, $\sigma = 0.04$ g cm^{-2}, $P = 7.7 \times 10^{-8}$ g cm^{-2} s^{-1} and $d = 0.8$ cm.

Appendix B. Two step model for thermally induced RH

Step 1. Calculation of the new global absolute humidity level

To perform the calculation we assume that the painting can be modeled as a closed system that contains a fixed total amount of moisture. In the initial situation the whole system will be at a single constant temperature T^i [°C] and at a single constant relative humidity level RH^i which is expressed as a fractional value between 0 (0%) and 1 (100%). The hygroscopic materials present within the system are treated as a number of sections *j*. If a single material, such as the canvas, will assume different temperatures along its surface, for each local temperature a separate section is assumed. After constant exposure to a temperature gradient a new temperature distribution will arise, and each section, with its associated dry mass M_j [g] is assumed to reach an individual constant local temperature T_j [°C]. The local temperature shift for a section *j* is denoted

$$\Delta T_j = T_j - T_i \qquad \text{[B1]}$$

To model the relation between a local surface relative humidity RH_j [0-1] and the equilibrium moisture content m_j of a section *j* with dry mass M_j, a simple linear equation is used. The direct proportionality between moisture content and relative humidity is characterised by the hygroscopicity factor α [dimensionless]. The absorption isotherms for canvas, wood and cardboard are known to show a downward shift upon increasing temperatures. To include this dependence a temperature dependent offset term $\beta \times \Delta T_j$ is added, where β [T^{-1}] is the temperature coefficient:

$$\frac{m_j}{M_j} = \alpha\, RH_j - \beta\, \Delta T_j \qquad \text{[B2]}$$

The hygroscopic behaviour of typical cellulose based materials [12] is relatively similar. In our calculations the values for hygroscopicity factor α and temperature coefficient β for all materials have been set to respectively $\alpha = 0.15$ and $\beta = 0.0008$ °C^{-1}.

At the initial condition of equal temperature T^i and relative humidity RH^i throughout the system, ΔT_j is zero and equation 2 simplifies to

$$\frac{m_j}{M_j} = \alpha\; RH^i \qquad \text{[B3]}$$

Using this equation, the total amount of moisture m_T present in the system, can now be estimated from the initial relative humidity by summing the contributions m_j from all individual hygroscopic sections.

$$m_T = \sum_j \left(\alpha\; RH^i\right) M_j \qquad \text{[B4]}$$

Note that the relatively small contribution of moisture present in the enclosed air volume is neglected here. Our assumption that the painting can be modelled as a system that is closed for moisture exchange results in a condition for the final local relative humidity values.

$$\sum_j \left(\alpha RH^i\right) M_j = m_T = \sum_j \left(\alpha RH_j^f - \beta \Delta T_j\right) M_j \qquad \text{[B5]}$$

We now proceed to calculate the final overall absolute humidity concentration C^f [g m^{-3}] that will result from reaching the final temperature distribution. The fact that a homogenous absolute humidity is assumed through the whole enclosed air volume provides a direct relation between the local temperature T_j at a section *j*, and the local relative humidity RH_j^f. By definition, the relative humidity is the ratio of the actual absolute humidity C^f over the saturation absolute humidity C_{sat} at a given temperature T:

$$RH_j^f = \frac{C^f}{C_{sat}(T_j)} \qquad \text{[B6]}$$

Substituting equations [5] in [6] it is possible to solve for the final homogeneous absolute humidity C^f that will be attained as a result of all local temperature shifts ΔT_j:

$$C^f = \frac{\sum_j \left(\alpha\; RH^i + \beta\, \Delta\, T_j\right) M_j}{\sum_j \left(\alpha\, \frac{1}{C_{sat}(T_j)}\right) M_j} \qquad \text{[B7]}$$

Step 2. Calculation of local relative humidity levels

Substitution of this result in equation 6 can now be used to predict the local relative humidity value RH_x for any local temperature T_x in the system. The relative humidity values are predicted both in the boundary layers at the hygroscopic surfaces, as well as for any other position in the system, for example at a sensor with a certain temperature, hanging free in the enclosed volume.

$$RH_x = \frac{C^f}{C_{sat}(T_x)}$$

[B8]

$$= \frac{\sum_j \left(\alpha RH^i + \beta \Delta T_j \right) M_j}{\sum_j \left(\alpha \frac{1}{C_{sat}(T_j)} \right) M_j} \left(\frac{1}{C_{sat}(T_x)} \right)$$

Essentially this equation tells us that moisture will migrate from warm to cold material sections in the painting and that the final relative humidities will depend on the relative masses of the material sections.