Full paper no: 74

Quantifying the Influence of Hygroscopic Materials in the Fluctuation of Relative Humidity in Museums Housed in Old Buildings

Cláudia Ferreira, M.Sc. [1]
Vasco Peixoto de Freitas, Full Professor [2]
Nuno M. M. Ramos, Assistant Professor [3]

[1] Engineering Faculty, Porto University, Portugal
[2] Engineering Faculty, Porto University, Portugal
[3] Engineering Faculty, Porto University, Portugal

KEYWORDS: *Hygroscopic Materials, Relative Humidity, Museums*

SUMMARY:
The preservation of artifacts in museum collections is profoundly affected by fluctuations in temperature and, especially, relative humidity. Since the late 19th century, many studies have been carried out into the best way to control hygrothermal conditions. Today, however, the focus is less upon visitors' comfort than upon ensuring the stability of relative humidity.

In old buildings located in temperate climate zones with strong thermal inertia, and which have low ventilation rate (relative to the volume and number of visitors), daily and seasonal hygroscopic inertia may help to assure the maintenance of RH stabilization conditions. That is to say, active systems may be dispensed with if the buildings' passive behaviour is used to best advantage.

This paper presents the validation of an advanced hygrothermal model by comparing numerical and experimental results of RH fluctuation in the reserves of a museum housed in an old building, located in Porto. The quantification of the influence of hygroscopic materials with different characteristics in stabilizing the relative humidity when ventilation flows are reduced is also presented.

1. Hygrothermal conditions in museums

One of the main functions of museums all over the world is the conservation of artefact collections. For this, it is essential to control the climate conditions (i.e. temperature and particularly relative humidity) inside the museum buildings, as a number of studies have shown (MacIntyre, 1934; Rawlins, 1942; Thomson, 1986).

In the rehabilitation of museums in old buildings, active systems for interior climate control have generally been favoured over passive ones. However, in countries with a temperate climate, such as Portugal, hygroscopic inertia combined with adequate ventilation may help control relative humidity fluctuations in old buildings without need for complex active systems.

Hygroscopic inertia refers to the capacity of a room to store excess moisture from the air and restore it to the atmosphere when the relative air humidity is low. The finishings and the stored materials used in the rooms are the main factors responsible for the storage and restitution of humidity. Hygroscopic inertia may be assessed over short periods of time (short-cycle hygroscopic inertia of rooms) and for longer periods (long-cycle hygroscopic inertia of rooms).

In the Building Physics Laboratory at the Faculty of Engineering, University of Porto – FEUP, important research has been carried out in the domain of daily (i.e. short-cycle) hygroscopic inertia in order to quantify the performance of render materials (through parameters that indicate their water vapour adsorption and restitution capacity), find models with which to assess the influence of daily hygroscopic inertia upon peaks of relative humidity, and develop experimental studies to measure the phenomenon and validate the models (Ramos, 2007; Freitas et al., 1988; Delgado et al., 2009; Ramos et al., 2009).

There have always been concerns about the climate conditions in museums. In the 1st century BC, Vitruvius mentioned the need to ensure wholesome conditions in the rooms where collections were kept (Casanovas, 2006). However, it was in the 20th century that the most significant advances were made in this area. In 1978, Garry Thomson published the book "The Museum Environmental", which gave priority to the museum's collections over its visitors and concluded that the control of relative humidity is much more important than the control of temperature (Thomson, 1986).

At the Ottawa conference of 1993 and 1994, Stefan Michalski contributed to an alteration of the dominant mindset by asserting that in museums there is no ideal relative humidity, but rather minimum and maximum values, and acceptable fluctuations that minimize the various types of deteriorations (Michalski, 1994). Till then, the reference values of temperature and relative humidity had been defined somewhat arbitrarily and were considered to be valid for any museum in any part of the world, whatever the exterior climate and the background of the collections and buildings.

In 1999, ASHRAE included in their manual for the first time a chapter devoted to museums, libraries and archives, in which they presented a methodology for the control of interior climate conditions based on reference values, maximum admissible fluctuations, and the risks and benefits for the collections, associated to each option (ASHRAE, 2007).

Between 1999 and 2001, a multidisciplinary European research project was under way which aimed to identify the main sources of risk to the cultural heritage due to the unconscious use of technology and mass tourism. The hygrothermal conditions were assessed in four museums exposed to different climate conditions and pollution levels, and it was concluded that museums located in historical buildings benefited from the heat and humidity storage action of their thick walls and the hygroscopic materials used in the renders inside the building. Air conditioning systems are generally designed for visitor comfort and often function only during the period in which the museum is open. However, this practice may be dangerous for the objects kept there, as it causes alterations in the temperature and humidity gradients over short spaces of time (Camuffo et al., 2001).

Another way of defining the hygrothermal conditions in museums is the confirmed fluctuation method, proposed by Stefan Michalski in a 2007 meeting organized by the Getty Conservation Institute in Tenerife. This method consists of defining the maximum temperature and relative humidity fluctuations to which the collection or object was subjected in the past, and respecting that interval (The Getty Conservation Institute, 2007).

In 2010, the CEN published a European norm (EN 15757), which established temperature and relative humidity specifications in order to limit the physical damage to organic hygroscopic materials (CEN, 2010). Then in 2012, the British Standards Institute published a specification that provided a series of requirements for the environmental conditions of storage, display and loan applicable to all types and sizes of collections (BSI Group, 2010).

It can be considered that, in addition to the developments summarized here, there is a need for an advanced hygrothermal approach to this problem that could enable the effect of hygroscopic inertia upon relative humidity peaks to be quantified.

2. Simulation vs Measurement: the hygrothermal behaviour of a museum

This study focuses upon the storage rooms used for paintings and sculptures in a Porto museum, located on the second floor of an old building. The storage rooms house works of art from the museum's painting and sculpture collection when they are not on display. They are visited sporadically by the technical staff. Ventilation is mechanical and consists of air extraction by a variable-speed ventilator in each room. The air extracted from the storage rooms comes from the exhibition gallery (A) through air inlet on the interconnecting doors.

The hygrothermal conditions in the storage rooms and exhibition gallery were monitored over the course of a year. This was done by distributing seven HOBO U12-011 dataloggers around the various rooms (FIG 1), located at a height of approximately 1.5 metres above the floor, which continuously recorded the temperature and relative humidity (FIG 2). The datalogger accuracy is, for temperature, ± 0.35 ºC in a range of 0 to 50 ºC, and for relative humidity, ± 2.5 % in a range of 10 to 90%.

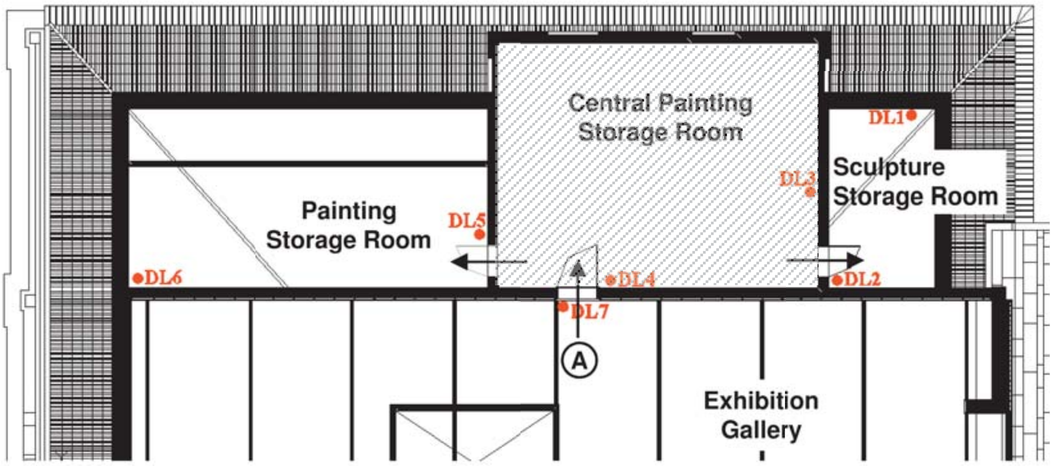


FIG 1. Location of the sensors in the museum storage rooms and exhibition gallery

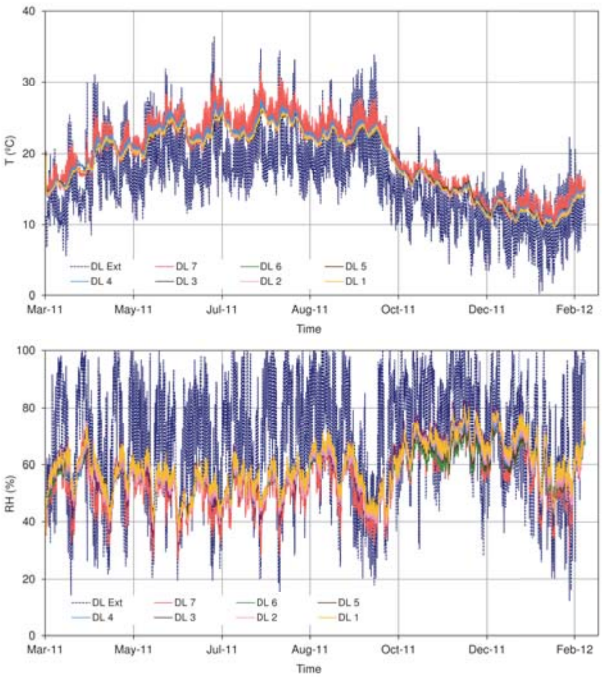


FIG 2. Temperature and relative humidity variations in the museum storage rooms and exhibition gallery over the course of a year

In order to assess the hygrothermal behaviour of museums and quantify the influence that the use of hygroscopic materials may have on the stabilization of relative humidity, an advanced hygrothermal numerical simulation model was selected. This was the *Wufi Plus*, a commercial programme developed by the *Fraunhofer Institut fur Bauphysik* to simulate the hygrothermal performance throughout the whole building. It was chosen because it had already been validated in various other studies (Woloszyn, M. and Rode, C. 2008).

In order to use any such advanced hygrothermal behaviour simulation programme, knowledge is required of the boundary conditions associated to the outside and inside climates, and the constitution of the building's envelope. Thus, data concerning the orientation of the building, geometry (FIG 3) of each component of the envelope (materials and their properties), exterior climate and ventilation were introduced into the model. The exterior climate used was obtained at the Meteorological Station of FEUP. This station is located in the same city with the same urban climate and at a distance of 2 km from the museum.

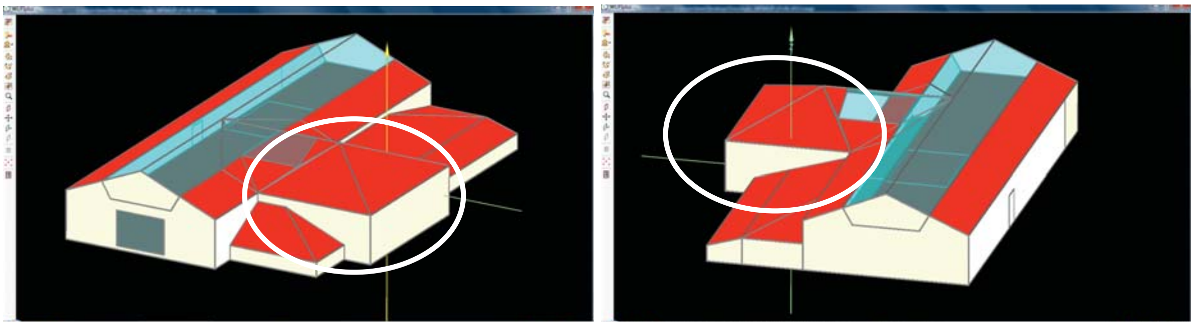


FIG 3. Model used for the exhibition gallery and storage rooms of the museum under study

The monitoring process provided the hourly temperature and relative humidity values, and the ventilation flows (extraction) in each storage room (TABLE 1). These flows were determined with the air speed in the air extraction opening, which was measured using an air speed and temperature measuring device associated to a *Micromec datalogger* for the acquisition and recording of data.

TABLE 1. Ventilation flows

Room	Type of ventilation	Source	Flow		ACH
			[m^3/s]	[m^3/h]	[h^{-1}]
Sculpture storage room	Mechanical	Central painting storage room	0.076	273.6	9.73
Central painting storage room	Mechanical	Exhibition gallery	0.056	201.6	0.98
Painting storage room	Mechanical	Central painting storage room	0.061	219.6	2.54

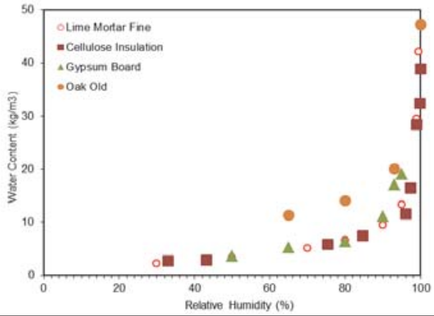
As regards the envelope, TABLE 2 gives a brief description of the constitution of each component and the material used in the final rendering. The properties of these materials were not determined experimentally. Instead, the database of the program *Wufi Pus* was used, which contained selected materials with similar properties to the finishing materials existing in the museum.

TABLE 2. Constitution of each component and respective finishing material

Component	Description	Finishing Material
Outer walls	Granite walls with ETICS	Lime Mortar with painting
Inside walls	Granite walls with lime-based rendering on both surfaces	Lime Mortar with painting
Roof of the sculpture and painting storage rooms	Pitched slab of reinforced concrete with thermal insulation and cellulose insulation on the interior surface	Cellulose Insulation with painting
Roof of the central painting storage room	Ceiling in gypsum board plus thermal insulation	Gypsum Board with painting
Floor	Reinforced concrete slab	Old Oak without varnish

TABLE 3 shows the properties of the finishing materials used for interior layer with higher relevance for the hygrothermal calculation.

TABLE 3. Main properties of the finishing materials

Properties	Lime Mortar	Cellulose Insulation	Gypsum Board	Old Oak
Bulk density	1785 kg/m^3	55 kg/m^3	850 kg/m^3	740 kg/m^3
Porosity	0.28	0.93	0.65	0.35
Specific heat capacity	850 J/kgK	2544 J/kgK	850 J/kgK	1600 J/kgK
Thermal conductivity	0.70 W/mK	0.036 W/mK	0.20 W/mK	0.1522 W/mK
Water vapour diffusion resistance factor	15	2	8.3	223
Hygroscopic sorption curves				

Using the advanced hygrothermal behaviour simulation programme, a series of simulations were carried out enabling the temperature and relative humidity to be estimated inside the different rooms. These were then compared to the measurements taken. For example, the measured and simulated temperature and relative humidity values inside the central painting storeroom are shown in FIG 4.

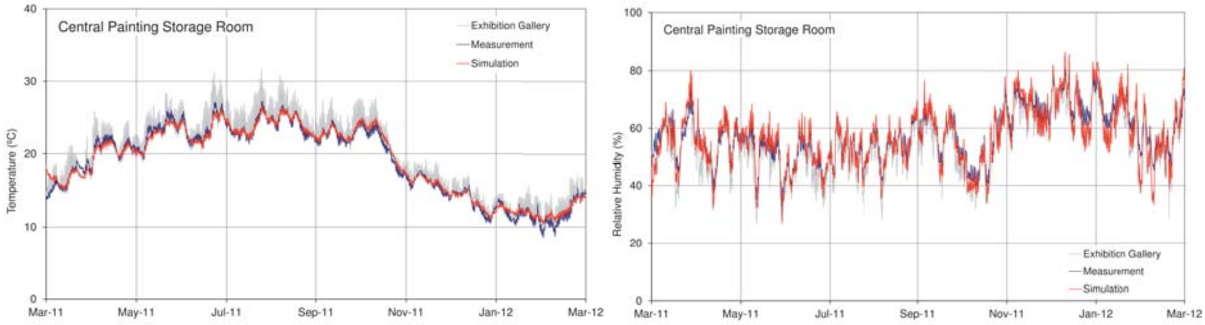


FIG 4. The measured and simulated temperature and relative humidity in the central painting store room

TABLE 4 shows the minimum, maximum and average temperature and relative humidity values obtained by measurement and simulation for the central painting storeroom.

TABLE 4. Minimum, maximum and average temperature and relative humidity

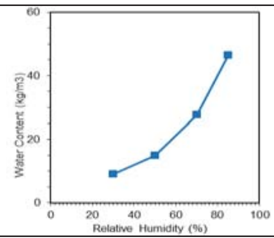
	Exhibition Gallery		Measurement		Simulation	
	T [ºC]	RH [%]	T [ºC]	RH [%]	T [ºC]	RH [%]
Minimum	9.15	26.35	8.51	32.92	10.39	27.198
Average	19.86	53.95	19.06	57.74	19.12	57.09
Standard Deviation	5.06	9.93	4.88	8.88	4.72	10.08
Maximum	31.75	80.64	27.25	80.82	26.69	86.25

From these figures and table, it is possible to observe that, on average, the simulated temperature differs from the measured temperature by about 0.5 ºC, while the simulated relative humidity differs from the measured by 2.5 % (calculus based in the hourly difference between measurement and simulation). Hence, the simulation and measured results are quite close, which validates the programme for the case study.

3. Assessment of the influence of hygroscopic materials

Having validated the numerical simulation model, the next step was to assess the influence of the use of hygroscopic materials upon the interior relative humidity stabilization. Thus, maintaining the ventilation flows and other conditions the same, the finishing materials of walls and ceilings of the rooms were changed for another material that was highly hygroscopic with high vapour permeability, namely spruce woodwool panels covered with mineral binders (M1). The properties of this material necessary for the hygrothermal calculation were inserted into the programme's database: bulk density (kg/m^3), porosity, specific heat (J/kgK), thermal conductivity (W/mK), water vapour diffusion resistance factor, and the respective hygroscopic sorption curve (TABLE 5).

TABLE 5. Properties of material M1

Spruce woodwool panels covered with mineral binders	Basic Material Data	Hygroscopic Sorption Curve
Bulk density	533 kg/m^3	
Porosity	0.50	
Specific heat capacity	1810 J/kgK	
Thermal conductivity	0.075 W/mK	
Water vapour diffusion resistance factor	1,1 (wc) e 3,2 (dc)	

The hygroscopic sorption curve and water vapour diffusion resistance factor enable the model to quantify the effect of the building materials upon the relative humidity stabilization. As shown in TABLE 5, the material used (M1) has good hygroscopic capacity in the 40 to 70% range of relative humidity (i.e. the recommended limits for relative humidity fluctuation inside museums).

FIG 5 shows the relative humidity variation of the central painting storage room, which resulted from the consideration of the original render materials and ACH – 0.98 h^{-1} (Simulation 1), the original render materials with a reduced ACH – 0.24 h^{-1} (Simulation 2), the adoption of buffering material M1 on the walls and ceiling and the original ACH – 0.98 h^{-1} (Simulation 3), and the adoption of buffering material M1 on the walls and ceiling with a reduced ACH – 0.24 h^{-1} (Simulation 4).

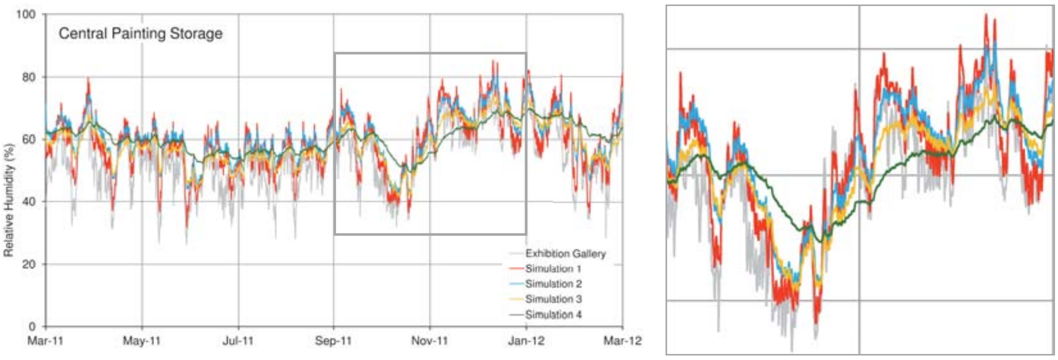


FIG 5. Comparison of relative humidity in the central painting storage room between: a) Simulation 1, which has a ACH of 0.98 h^{-1} and the original render materials; b) Simulation 2, with an ACH of 0.24 h-^{1} and the original render materials; b) Simulation 3, which has an ACH of 0.98 h^{-1} and buffering material M1 on the walls and ceiling; d) Simulation 4, which has an ACH of 0.24 h-^{1} and material M1 on the walls and ceiling

The use of buffering materials (FIG 5) which optimize hygroscopic inertia, improve the relative humidity stabilization. If the ventilation in the central painting storage room is reduced from 0.98 h^{-1} to 0.24 h^{-1}, the hygroscopic inertia effect is clearly visible.

TABLE 6 shows the minimum, maximum and average values of relative humidity in the central painting storage room obtained in the different simulations. It also shows a parameter called Relative Humidity Stabilization (RHS), which enables the performance of the various solutions on the relative humidity stabilization to be quantified, resulting from the sum of the different absolutes between average relative humidity and hourly relative humidity.

TABLE 6. Minimum, maximum, average relative humidity and RHS

Relative Humidity	Gallery	Simulation 1	Simulation 2	Simulation 3	Simulation 4
Minimum	26.35	27.19	42.50	41.56	49.38
Average	53.95	57.09	60.68	58.29	60.17
Standard Deviation	9.93	10.08	7.56	6.79	4.66
Maximum	80.64	86.25	81.25	74.38	69.84
$RHS = \sum_i \left\lvert \overline{RH} - RH_i \right\rvert$	70 738	70 073	52 795	48 469	33 794

From this one can conclude that:

- When the ACH value is around 1 h^{-1} and buffering material M1 is used on the walls and ceilings (Simulation 3), the value of parameter RHS reduces by 30 % compared to when the original materials are used (Simulation 1);
- When the ACH value is around 0.25 h^{-1} and buffering material M1 is used on the walls and ceilings (Simulation 4), the value of parameter RHS drops by 36 % compared to when the original materials are used (Simulation 2), and by 52 % compared to when the original materials are used and when a ACH value around 1 h^{-1} is considered (Simulation 1);
- When the ACH value is around 0.25 h^{-1} and buffering material M1 is used on the walls and ceilings (Simulation 4), the difference between the maximum and minimum relative humidity is 20 % compared to the 59 % of Simulation 1.

4. Conclusions

The main achievements and conclusions of this study are the following:

- The temperature and the relative humidity of a painting storeroom in a Porto museum were monitored. The ventilation air was admitted from the exhibition gallery with an ACH of 0.98 h^{-1}; the finishing materials used on the walls, ceiling and floor were lime mortar, gypsum board and old oak respectively;
- An advanced hygrothermal simulation model was used and validated with experimental results;
- The properties of buffering material M1 (spruce woodwool panels covered with mineral binders), were measured and were found to be the following: moisture content of 12 to 40 kg/m^3 for relative humidity values of 40 % to 80 %; water vapour diffusion resistance factor (μ) of 1.1 in the wet cup test and 3.2 in the dry cup test;
- When this particular buffering material was placed on the walls and ceiling of the storeroom, the difference between the maximum and minimum interior relative humidity changed from 59% to 33% for a ACH of 0.98 h^{-1};
- A parameter defined as Relative Humidity Stabilization (RHS), which reflects the performance of various solutions in stabilizing relative humidity, was quantified. This parameter is reduced by 59% compared to the reference situation (Simulation 1) when the finishing materials and ventilation are optimized.

5. Acknowledgements

Cláudia Ferreira would like to thank Fundação para a Ciência e Tecnologia (FCT), Ministério da Ciência, Tecnologia e Ensino Superior, Portugal, for financial support through the grant SFRH/BD/68275/2010.

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