The Influence of Mass Tourism and Hygroscopic Inertia in Relative Humidity Fluctuations of Museums Located in Historical Buildings

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Abstract

The preservation of artefacts in museum collections is profoundly affected by fluctuations in temperature and relative humidity. This work presents the results of an experimental laboratorial study, conducted in a flow chamber to demonstrate the enormous potential of hygroscopic materials in stabilizing interior relative humidity. In order to assess the risk of mass tourism and hygroscopic inertia of finishing materials, associated with the hygrothermal behavior of museums, an analysis of several numerical scenarios, with a different number of visitors per hour, and finishing materials, in order to quantify the risks associated with the fluctuations of relative humidity. The results of sensitivity studies performed are presented for the case of a museum in Porto.

Keywords

Mass Tourism, Hygroscopic Inertia, Relative Humidity, Museums, Collections Preservation.

Introduction

One of the main functions of museums all over the world is the conservation of artefact collections. This complex work includes, among other things, the control of the interior climate conditions (i.e., temperature, T, and particularly relative humidity, RH) inside the museum buildings (MacIntyre, 1934; Rawlins, 1942; Thomson, 1986).

In the rehabilitation of museums in ancient buildings, active systems for interior climate control have frequently been favored 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 ancient buildings without the 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 one of 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 Laboratory of Building Physics, at Faculty of Engineering of 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 vapor 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 (Freitas & Abrantes, 1988; Ramos, 2007; Delgado, Ramos, & Freitas, 2009; Ramos & Freitas, 2009).

It is crucial the control of relative humidity and temperature fluctuations to preserve the museum's collections. Today, there are advanced hygrothermal simulation tools to predict the climate inside, taking into account the geometry of the building, the finishing materials, the ventilation, and the occupancy.

In the last years, LFC-FEUP research group has validated the hygrothermal numerical simulation model (Wufi-Plus), in different museums, by comparing numerical and experimental results of interior climate, using for this purpose several sensors.

The mass tourism has led to an exponential increase in museums occupancy with serious consequences on indoor temperature and relative humidity change that may put at risk the preservation of the exhibited collections.

In order to assess the hygroscopic inertia of finishing materials associated with the hygrothermal behavior of museums, an advanced hygrothermal numerical simulation model was used to evaluate those risks, for a generic museum room (model) located in a historical building of different Portuguese climatic zones.

Laboratory Experiments

RHS Parameter

Relative humidity stabilization parameter (*RHS*) consists of the sum over a year of the absolute differences between the 90 days mean seasonal relative humidity and the relative humidity in each hour (Ferreira, Freitas, & Delgado, 2019). The parameter is critical, fundamentally, for organic materials, but should be in mind that other important parameters should be considered.

$$RHS = \sum_{i=1}^{8760} \left| \overline{RH}_{i,seasonal} - RH_i \right|$$

(1)

This parameter allows quantifying the greater or lesser relative humidity stabilization over a year. To estimate the seasonal change in the climate, a running average ($\overline{RH}_{i,seasonal,90d}$) is calculated for each hour and consists of the arithmetic average of the hourly values of 45 days or 1080 hours before, and 45 days or 1080 hours after (see Eq. (2)). This period is centered, which means for each value looking back one month and a half and looking forward one month and a half.

$$\overline{RH}_{i,seasonal,90d} = \frac{1}{2161} \sum_{a=i-1080}^{i+1080} RH_a$$

(2)

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Materials and Methods

A coating material, normally, used in the rehabilitation of historical buildings, was select to evaluate the hygroscopic behavior, as well as the contribution to the control of indoor relative humidity. The material selected, with a thickness of 15mm, was a 1.5mm diameter wood fibers panels agglomerated with white cement (Material B).

From the experimental results reported in Table 1 it is possible to observe that Material B is very permeable to water vapor, and the water vapor permeability, δ_p, is dependent on the prevailing relative humidity and generally changes rapidly at high RH. This material presents a greater amount of adsorbed water vapor (MBV) for the relative humidity range of 33% to 75%, with 94.7 g/m^2 (2.25 g/m^2%RH). Nordtest report (Rode et al., 2005) classified the capacity of materials to buffer moisture of indoor environment, according to their MBV obtained from MBV test with a range of 33%-75% RH. As so, Material B is classified as excellent material (MBV>2 g/m^2%RH) to buffer moisture. Finally, these experiments allowed concluding that Material B presents a hygroscopic capacity of 0.07 kg/m^2 (calculated by the product of equilibrium moisture content with material density and thickness at different RH's) for a relative humidity variation between 50% and 70%.

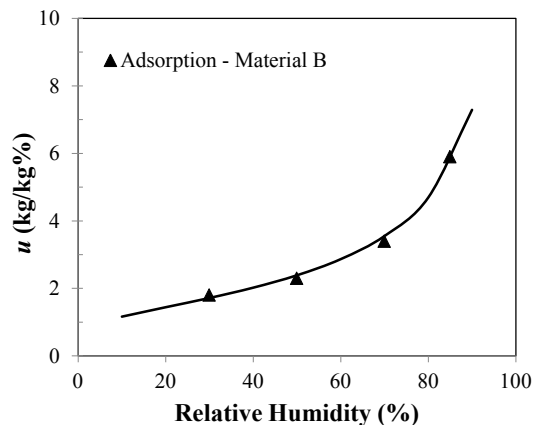| Properties	Material B
Density, r (kg/m^3)	450
Porosity, e (-)	0.38
Heat capacity, c_p (J/kgK)	2800
Thermal conductivity, l W/mK)	0.100
Water vapor permeability, δ_p (kg/msPa)	$4.13\pm0.21\times10^{-11}$ (dry) $1.37\pm0.51\times10^{-10}$ (wet)
Water vapor diffusion resistance factor, μ (-)	4.63±0.24 (dry cup) 1.40±0.05 (wet cup)
Equivalent air layer thickness, s_d (m)	0.08±0.012 (dry cup) 0.02±0.001 (wet cup)
Moisture Buffer Value, MBV (g/m^2.%RH)	2.25 (or 94.6 g/m^2) (Excellent)
Hygroscopic sorption curve (μ, φ)	

Table 1 – Hygroscopic properties of the selected material.

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The flux chamber (see Figure 1), with dimensions 1500x524x584mm³, was installed in a climatic chamber with controlled temperature (T in the range 15 ºC-35 ºC) and relative humidity (RH in the range 30%-90%). The temperature and relative humidity could be controlled by fixing values or using programmable cycles including the variation of one or both parameters. The ventilation system presents two points, inside the flux chamber, to extract the air and an inlet on top allows for the air to get in and at the same time prevents pressure differences. The flux chamber inlet air comes directly from the climatic chamber and its characteristics are known, whereby infiltration through the openings does not affect the overall balances of heat, air, and moisture. The air flux value is controlled by flow meters with a range of air exchange rate (ach) of 0.26 - 17h^{-1}.
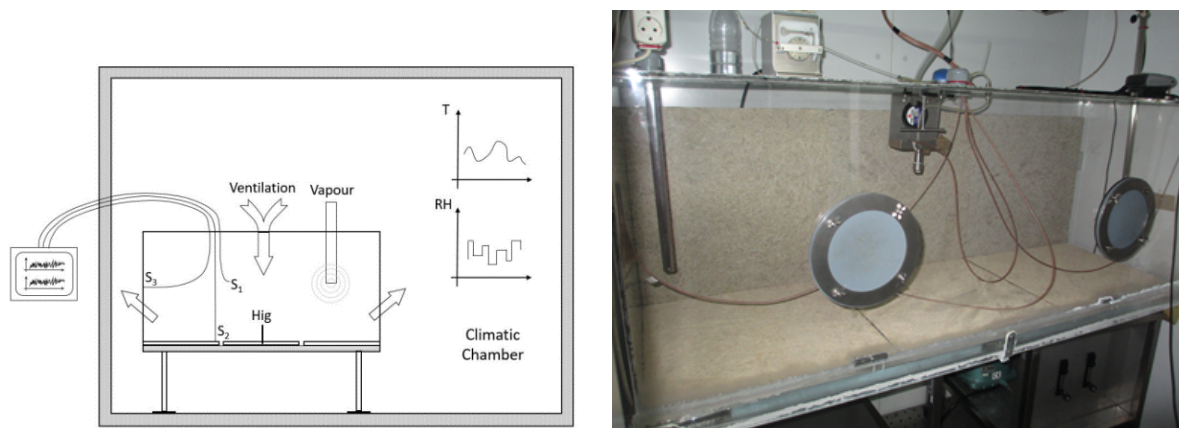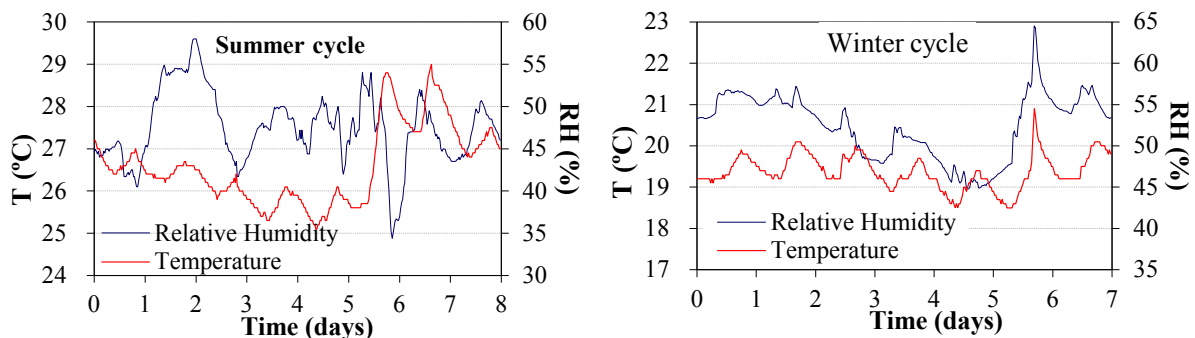

Figure 1 – Sketch of the flux chamber.

Figure 2 – Flux chamber exterior climate (summer and winter cycles).

Ref.	Climatic chamber	Flux chamber	
	Cycle	*ach* (h^{-1})	Hygroscopic material
Conf. 2.1	Summer	0.26	--
Conf. 2.3	Summer	0.65	--
Conf. 2.5	Summer	0.26	0.75 m² of Material B
Conf. 2.7	Summer	0.65	0.75 m² of Material B
Conf. 2.2	Winter	0.26	--
Conf. 2.4	Winter	0.65	--
Conf. 2.6	Winter	0.26	0.75 m² of Material B

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| Conf. 2.8	Winter	0.65	0.75 m² of Material B

Table 2 – Configurations tested in the flux chamber.

The flux chamber was subject to a different cycle of exterior climate generated by the surrounding climatic chamber, and it was tested with an hourly air change rate of 0.26 h⁻¹ and 0.65 h⁻¹ (values selected in accordance with the flux chamber limitations), and an area of 0.75 m² of hygroscopic coating material. The exterior climate was defined based on the average climatic conditions inside a museum located in the city of Porto, and consisted of the definition of summer and winter cycles, as sketched in Figure 2. The tested configurations analyzed in the flux chamber are described in Table 2.

Experimental Results

In Figure 3 and Table 3 are presented the results of the temperature and relative humidity obtained for the tested configurations, with different air change rate, and for the summer cycle and winter cycle. The main conclusions were:

(1) The test results carried out in the flux chamber demonstrate that the introduction of the hygroscopic coating material (Material B) influences the fluctuation of the relative humidity inside the flux chamber;

(2) This influence is visible when comparing the variation between the maximum and minimum relative humidity - ΔRH of Conf. 2.1 and Conf. 2.5 or Conf. 2.3 and Conf. 2.7 (summer cycle); and Conf. 2.2 and Conf. 2.6 or Conf. 2.4 and Conf. 2.8 (winter cycle), with different air change rates.
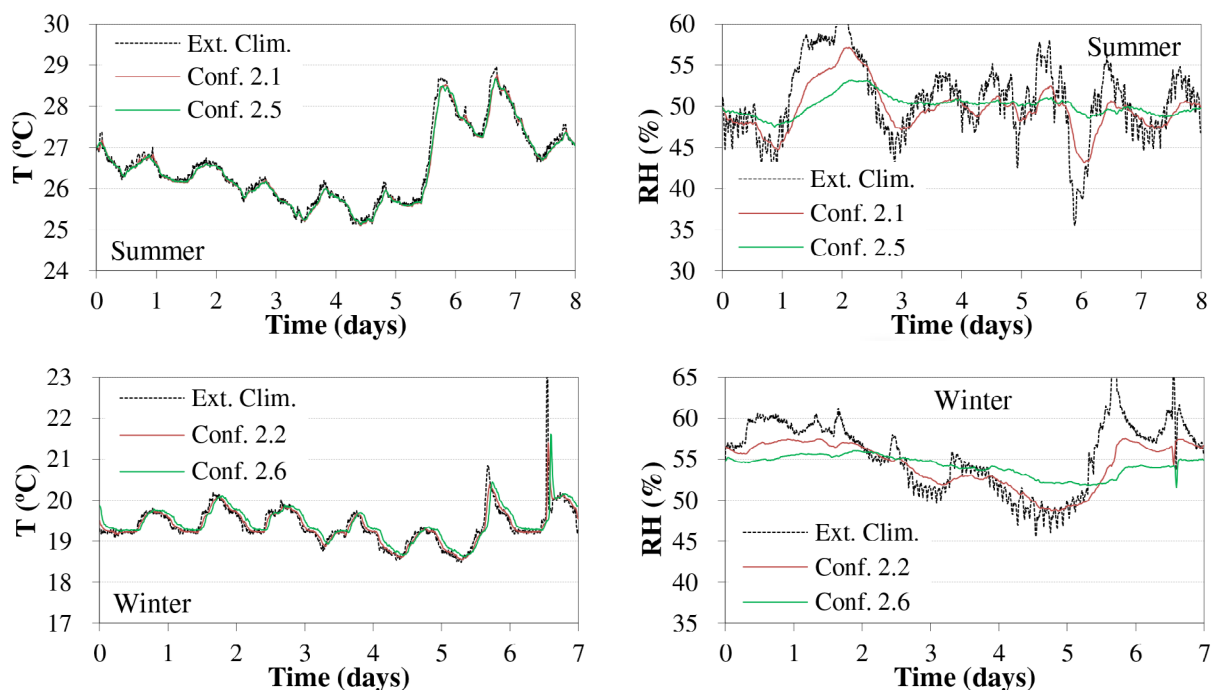
Figure 3 – Temperature and relative humidity variation observed, with ach=0.26h^{-1}, in: (a) Summer cycle and (b) Winter cycle.

Hygroscopic capacity (C_{apHyg}) was calculated for the different configurations tested using Equation (3), and the results obtained described in Table 3:

$$C_{apHyg}\left(g/m^3\%RH\right) = \frac{\sum\limits_{i} MBV_i \times S_i}{V}$$

(3)

where MBV_i is the Moisture Buffer Value of the finishing material [g/m²%HR], S_i is the surface area [m²] and V is the volume [m³] of the flux chamber.

Relative humidity	Ext. Clim.	2.1 0.26h^{-1}	2.3 0.65h^{-1}	2.5 0.26h^{-1}	2.7 0.65h^{-1}	Ext. Clim.	2.2 0.26h^{-1}	2.4 0.65h^{-1}	2.6 0.26h^{-1}	2.8 0.65h^{-1}
C_{apHyg} (g/m³%RH)	--	0.00		3.68		--	0.00		3.68	
Maximum	62.34	57.16	58.91	53.16	54.45	69.93	57.51	60.61	56.05	57.44
Minimum	35.48	43.17	40.66	47.47	47.22	45.06	48.71	48.05	51.58	51.25
Average	50.76	49.70	49.84	50.08	50.26	55.66	54.37	54.69	54.24	54.97
St. Dev.	4.60	2.816	3.547	1.21	1.596	4.253	2.765	3.359	1.209	1.846
ΔRH	26.86	13.99	18.25	5.69	7.23	24.87	8.79	12.56	4.47	6.19
RHS	--	21286	26051	10513	14166	--	21286	26051	10513	14166

Table 3 – Hygroscopic capacity, maximum, minimum and average values of relative humidity obtained in the flux chamber, for summer and winter cycle, with different air change rate.

Numerical Analysis

The main objective is to evaluate the performance of the museum rooms with different hygroscopic finishing materials and ventilation rates. The boundary conditions associated with the outside and inside climates and the constitution of the building's envelope are required. Thus, data concerning the building model (see Figure 4), the geometry of the envelope (materials and their properties), exterior climate ventilation and internal gains (number of visitors) were introduced into the model.

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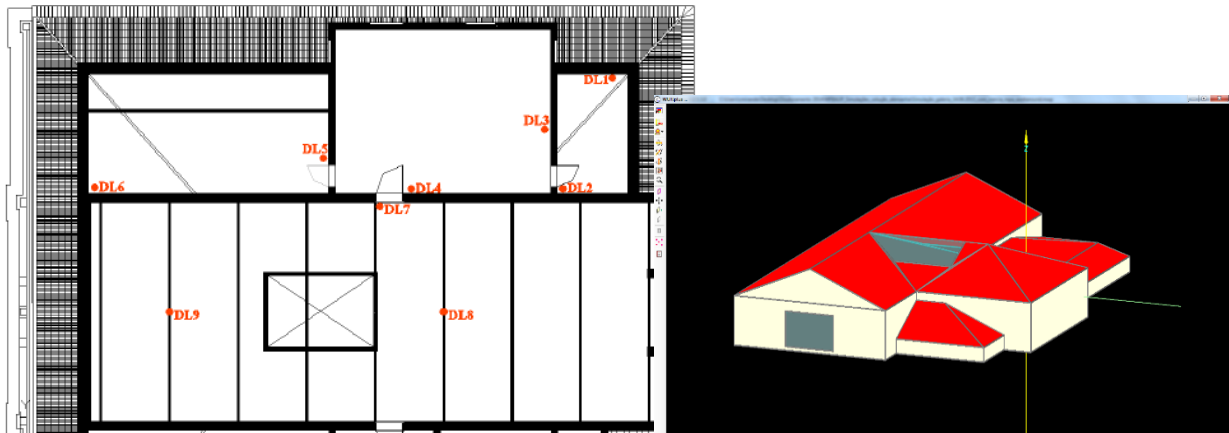Cláudia Ferreira; Vasco Peixoto de Freitas & João Delgado

Figure 4 – Museum room plant and the model building used in this study.

In accordance with the experimental results, a preliminary numerical study was conducted using Wufi-Plus hygrothermal model of advanced numerical simulation (IBP, 2010). The main objective is to evaluate the performance of the museum rooms with different hygroscopic finishing materials, ventilation rates, and occupancy, specifically in terms of temperature and relative humidity fluctuations. For this purpose, Table 4 presents several variables of the outdoor climate tested according to the specific weather file used. In this preliminary analysis, only Porto city was considered.

District	Climatic zone	Temperature [ºC]			Relative Humidity [%]		
		Mean	Maximum	Minimum	Mean	Maximum	Minimum
Porto	I2 – V1	15.2	38.4	0.3	73.3	99.0	9.40

Table 4 – External climate data considering the climatic file used in the simulation (annual values).

Component	Description	Finishing material
Outer walls	Granite walls with ETICS	Lime mortar with painting
Inner walls	Granite walls with lime-based rendering on both surfaces	Lime mortar with painting
Roof	Ceiling in gypsum board plus thermal insulation	Gypsum board with painting
Floor	Reinforced concrete slab	Old Oak without varnish

Table 5 – Constitution of each component and respective finishing material (base scenario).

Properties	Lime mortar	Gypsum board	Old Oak	Material B

Bulk density [kg/m³]	1785	850	740	
Porosity [-]	0.28	0.65	0.35	
Specific heat capacity [J/kgK]	850	850	1600	
Thermal conductivity [W/mK]	0.70	0.20	0.1522	
Water vapor diffusion resistance factor [-]	15	8.3	223	
Hygroscopic sorption curve				See Table 1

Table 6 – Main properties of the hygroscopic finishing materials used in numerical simulation.

As regards the envelope, Table 5 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 6 shows the properties of the finishing materials used for the interior layer with higher relevance for the hygrothermal calculation. The area of the hygroscopic finishing material (Material B) used was 168.4m².

Ventilation rates (0.24h⁻¹ and 0.98h⁻¹, typical values of the museum room analyzed) were specified as well as internal gains resultant from lighting, 9W/m² during opening hours (from 10:00 to 18:00) and the only day closed for visitors was considered to be Monday) and 2 W/m² selected for the remaining period. Regarding occupancy, different numbers were chosen (5, 10 and 20 visitors per hour), and considering that each visit has a duration of 20 min and a typical year with 308 days of being open to the public, it results in a range of visitors annually between 36960 and 147840.

Several parameters were used to obtain the internal gains, namely, a metabolic rate of 1.28 met and a heat gain of 134W, in which 60% is sensible heat and 40% is latent heat. Sensible heat is directly related to temperature (50% radiant and 50% convective). Considering the ventilation flow of 0.26h⁻¹ and taking into account that each visitor releases 70 g/h of water vapor in the duration of 8h (BS 5250, 2011), the internal water vapor gain is given by:

$$Inter.Gain = \frac{n.w.h}{ach.V.24}$$

(4)

where n is the number of visitors, ω the water vapor produced by each visitor (70g/h), h the number of hours of the visit (8h), *ach* the ventilation rate ($0.26h^{-1}$), V the room volume ($206m^3$) and 24 the factor used to obtain the mean hygrometry.

Results and Discussion

Tables 7 and 8 present the indoor climate characterization, specifically concerning temperature and relative humidity, in order to better perceive the implications associated with the different variables analyzed in performed simulations.

Figures 5 and 6 show, as an example for Porto, the seasonal temperature, and relative humidity obtained for the different scenarios studied. It is possible to observe an increase of temperature and RH with the number of visitors, however, the increase of RH is significantly lesser when the museum room used hygroscopic materials, namely with an ach=$0.24h^{-1}$. More in detail, the results show:

(1) An increase of the average temperature and relative humidity with the number of visitors per hour, for an *ach*=$0.24h^{-1}$, however, for an *ach*=$0.98h^{-1}$, the average temperature increases, and the *RH* decreases;

(2) When the *ach* value is $0.24h^{-1}$ and buffering material B is used on the walls and ceilings, the value of parameter RHS drops, in average, by 27% compared to when the original materials are used;

(3) When the *ach* value is $0.98h^{-1}$ and buffering material B is used the value of parameter RHS reduces, in average, by 22% compared to when the original materials are used;

(4) When the *ach* value is $0.24h^{-1}$ and buffering material B is used on the walls and ceilings, the difference between the maximum and minimum relative humidity ranged between 28.4% and 40.0% compared to the range between 38.1% and 53.3%.

When the ach value is $0.98h^{-1}$ and buffering material B is used the difference between the maximum and minimum RH ranged between 45.8% and 65.3% compared to the range between 53.8% and 71.9%.

Variables / Nº Visitors per hour 0		Base scenario				Base scenario + Mat. B			
		5	**10**	**20**	**0**	**5**	**10**	**20**	
Min	**T (ºC)**	10.3	11.3	12.3	14.2	10.7	12.1	13.3	15.8
	RH (%)	33.7	40.0	45.0	50.6	38.3	45.8	49.7	54.5
Max	**T (ºC)**	25.2	27.1	28.9	32.2	25.8	28.2	30.6	35.0
	RH (%)	85.3	93.3	95.9	99.0	76.6	81.7	86.1	91.4
Average	**T (ºC)**	17.7	19.0	20.2	22.6	18.3	20.1	21.7	24.8
	RH (%)	62.0	69.0	74.8	83.3	59.7	64.7	68.5	72.5
St. Dev.	**T (ºC)**	3.9	3.9	4.0	4.0	3.9	3.9	4.0	4.1
	RH (%)	9.1	8.6	8.9	9.5	6.6	6.0	6.4	7.1

Table 7 – Temperature and relative humidity results for Porto with different visitors per hour and *ach*=$0.24h^{-1}$.

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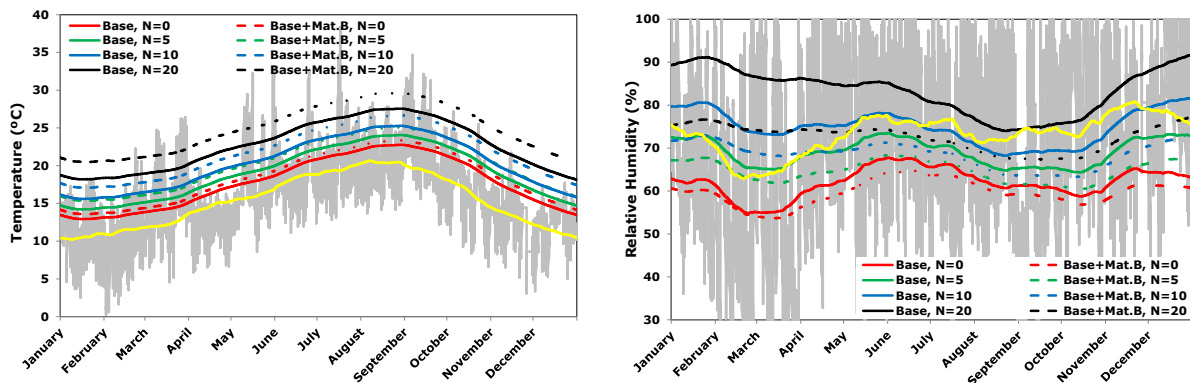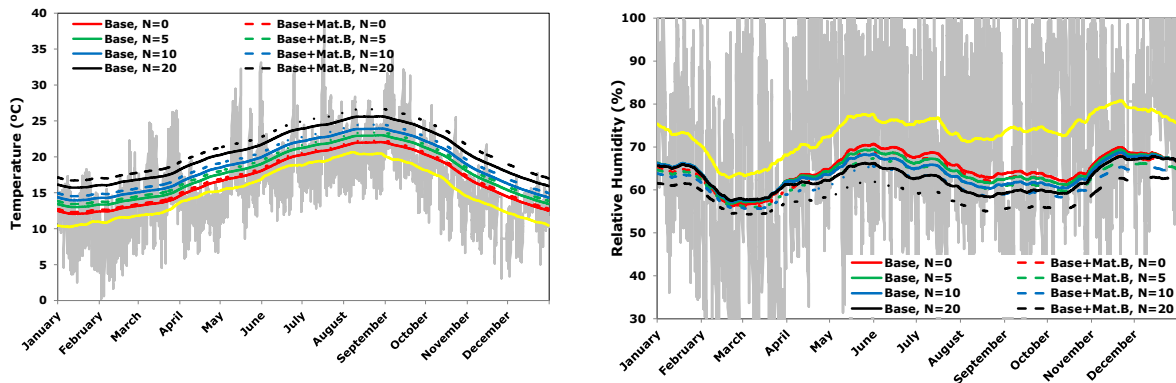Cláudia Ferreira; Vasco Peixoto de Freitas & João Delgado

Figure 5. Numerical results for Porto, with and without buffering materials, different number of visitors per hour, and *ach*=0.24h⁻¹ (seasonal exterior T and RH marked as a yellow line).

Variables / Nº Visitors per hour 0		Base scenario				Base scenario + Mat. B			
		5	**10**	**20**	**0**	**5**	**10**	**20**	
Min	**T (ºC)**	8.8	9.6	10.4	11.8	8.6	9.4	10.3	12.0
	RH (%)	23.8	27.2	26.7	25.8	25.9	29.2	28.8	27.2
Max	**T (ºC)**	25.5	26.9	28.2	31.0	26.0	27.8	29.5	33.0
	RH (%)	95.6	95.6	95.5	95.0	91.2	89.4	87.7	84.7
Average	**T (ºC)**	16.9	17.9	18.8	20.5	17.2	18.3	19.4	21.6
	RH (%)	64.9	64.3	63.6	62.5	63.7	62.5	61.2	58.5
St. Dev.	**T (ºC)**	4.0	4.1	4.1	4.2	4.0	4.1	4.2	4.4
	RH (%)	12.5	11.8	11.5	11.4	10.6	9.9	9.4	9.0

Table 8 – Temperature and relative humidity results for Porto with different visitors per hour and *ach*=0.98h⁻¹.

Figure 6 – Numerical results for Porto, with and without buffering materials, different number of visitors per hour, and *ach*=0.98h⁻¹ (seasonal exterior T and RH marked as a yellow line).

Conclusions

This work presents a study of the influence of hygroscopic materials in stabilizing the relative humidity when ventilation flows are reduced.

When this particular buffering material was analyzed numerically, as part of the walls and ceiling of the museum room, the difference between the maximum and minimum interior

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relative humidity decreases in more than 10%, for an ach=0.24h^{-1}. These results show that it is possible to use passive technique for controlling/mitigating relative humidity in storage rooms, inside museums, when ventilation flows are reduced.

References

BS 5250 (2011). *Code of practice for control of condensation in buildings*. British Standards Institution.

Delgado, J. M. P. Q., Ramos, N. M. M., & Freitas, V. P. (2009). Can moisture buffer performance be estimated from sorption kinetics? *Journal of Building Physics, 29(4)*, 281-299.

Ferreira, C., Freitas, V. P., & Delgado, J. M. P. Q. (2019). Hygroscopic Materials Influence in the Fluctuation of Relative Humidity in Museums Located in Historical Buildings. *Studies in Conservation* (online). https://doi.org/10.1080/00393630.2019.1638666.

Freitas, V. P., & Abrantes V. (1988). Étude expérimentale de l'humidité de l'air dans l'intérieur dês bâtiments. Influence du comportement hygroscopique des matériaux. In *Proceedings of Healthy Buildings'88*, CIB, Volume 2 (pp. 201-209).

IBP-Fraunhofer-Institut für Bauphysik (2010). Fundamentals of WUFI-Plus. In *Seminar: Simultaneous Calculation of Transient Hygrothermal Conditions of Indoor Spaces and Building Envelopes*. Holzerkirchen, Germany.

MacIntyre, J. (1934). *Some problems connected with atmospheric humidity. Some notes on atmospheric humidity in relation to works of art*. Courtauld Institute of Art, London, UK, 7-16.

Ramos, N. M. M., & Freitas, V. P. (2009). An experimental device for the measurement of hygroscopic inertia influence on RH variation. *Journal of Building Physics, 33(2)*, 157-170.

Ramos, N. M. M. (2007). *The importance of hygroscopic inertia in the hygrothermal behaviour of buildings* (Doctoral dissertation). Faculdade de Engenharia da Universidade do Porto, Portugal.

Rawlins, F. I. G. (1942). The control of temperature and humidity in relation to works of art. *Museums Journal, 41*, 279-283.

Rode, C., Peuhkuri, R., Mortensen, L., Hansen, K., Time, B., Gus-Tavsen, A., Svennberg, K., Arfvidsson, J., Harderup, L., Ojanen, T. & Ahonnen, J. (2005). *Moisture buffering of building materials*. Report BYG-DTU R-126, Department of Civil Engineering, DTU, Lyngby, Denmark.

Thomson, G. (1986). *The museum environment*. Second edition, Oxford: Elsevier Butterworth-Heinemann.

Acknowledgments

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