Ventilation and RH control in museum showcases

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Abstract

Museum showcases represent a peculiar confined space were ventilation and indoor climate conditions play an important role. Conservation of the works of arts, in fact, requires a control of the environmental parameters, with a tolerance usually far tighter than that required for assuring the comfort of people.

A number of laboratory measurements have been performed on small experimental showcases to analyze the influence of air tightness and gas permeability on the passive control of the RH inside the container (pressurization tests, tracer gas measurements and temperature/relative humidity response tests have been performed). Furthermore, real showcases, operating under actual museum conditions, have been studied by monitoring, for medium long time, indoor/outdoor environmental parameters.

In the paper the set-up of the laboratory experimental procedure and the measurement results are presented and critically analyzed. These laboratory experiences are then compared against field measurement results.

Keywords: museum showcases, artworks preservation, air tightness, gas permeability, laboratory measurements, thermo-hygrometric control, environmental conditions monitoring, buffer materials, passive RH control.

Introduction

The conservation of works of art is largely influenced by the conditions of the indoor environment where the objects are exhibited or preserved. In fact, the conservation conditions of materials (both in general and, in particular, for hygroscopic substances, such as paper, wood and canvass) depends strongly on the level of the air temperature and relative humidity of the surrounding environment. Therefore, the environmental control assumes a remarkable role in the preventive conservation. The environmental parameters, such as relative humidity, temperature, but also light and dust, if not properly controlled, can cause or accelerate the deterioration of works of art.

In recent times, in Europe and Italy, the emanation of standards and guide-lines [1, 2, 3] has contributed to rise the attention of museum staff to the microclimatic control. Optimal values of the ambient parameters, that can be used as a reference by curators in absence of other specific indications, have been assessed for different categories of materials.

The actual achievement of these optimal values, however, can be very difficult due to the specific features of museum buildings and their installations. In such conditions, and/or when mixed collections are displayed in the same room, the adoption of suitable museum showcases can be a valid alternative to allow a suitable control of thermo-hygrometric parameters.

In order to perform as expected, museum showcases must, nevertheless, meet several requirements. Among the other it is possible to mention:

- security, that is protection against acts of vandalism and robbery,
- safety, that is protection against various risk (fire, earthquake, …),
- optimal fruition of the displayed collection,
- proper conservation of artworks, that is control of relative humidity, IAQ and temperature.

In relation to the last requirement, it is of paramount importance to design a museum showcase capable of reducing and delaying the time variation of the indoor environmental parameters caused by the external conditions (i.e. the ones in the room). A good showcase envelop, with high thermal insulation and low air (gases and water vapor) permeability, can provide a first, significant measure to make, on the short and medium time, the internal conditions (micro-environment) the least influenced by the external conditions (macro-environment). Construction materials and techniques play a primary role as far as the envelope performances are concerned [4] and, hence, largely affect the number of air exchanges between showcases and museum indoor environment. Through the use of a suitably optimized showcase envelopes it is possible to exert a first, effective, control of the environmental conditions for preservation. However, it has to be underlined that, on the long period of time, the values of micro- and macro-environment parameters will tend to be the same (i.e. they will swing around the same average value). In order to further improve the control of the internal temperature and relative humidity the adoption of supplementary measures is therefore required.

To keep inside the showcase an average value of the thermo-hygrometric parameters constantly different from that in the room, two different strategies can be used:

- *passive control* (nowadays this approach is only limited to the relative humidity control),
- *active control* (both relative humidity and temperature are accurately controlled via a mechanical HVAC system).

Passive control is carried out by introducing in the showcase some buffer or hygroscopic materials (typically silica-gel salts) that, pre-conditioned at the desired RH level, adsorb and release water vapour and help in stabilising the relative humidity. This type of devices offers several benefits compared to active control; in particular it requires low operating and maintenance cost and its action is intrinsically safe (a fault in an active control system, in fact, can determine rapid and large variations of temperature and relative humidity inside the showcase, the worst scenario as far as the conservation of works of art is concerned).

However, buffer materials have a limited life span and periodically, the “exhausted” material has to be changed and re-conditioned.

It is well known that the “air change rate” plays a fundamental role in determining the performance of a showcase and the life span of buffer materials [5]. Less obvious is the fact that the usually adopted “air change rate” parameter actually includes, not only the effect of ventilation, but also the diffusive phenomena, i.e. the gas exchange between the indoor/outdoor of the showcase due to the gas permeability of materials.

It has to be noted that the situation is analogous to the building sector, but in this last case the influence of ventilation phenomena is of orders of magnitude larger than diffusion, being the air tightness of rooms far worse than that of showcases. Furthermore, the surface-to-volume ratio increases by decreasing the size of the system and hence, the surface related phenomena (like gas diffusion) will play a major role in case of small enclosures.

Aims of this work were:

- to analyze the influence of air tightness and gas permeability on the passive control of the relative humidity inside museum showcases,
- to set-up, verify and propose test procedures for assessing the showcase performance,
- to deepen the knowledge of buffer material behavior.

For this sake, some experimental showcases, made of different materials and with various construction techniques, have been tested in laboratory. Moreover, investigation were also performed in the field by analyzing the behavior of real museum showcases and by testing different strategies for improving their performance.

Pollutants mass balance and influence of ventilation/diffusion on showcase indoor environment

As it has been discussed in the previous section, the common belief among museum curators is that air tightness of showcases is, practically, the only relevant features as far as the envelope performance are concerned. Consequently great care is paid by manufacturers in building well "sealed" containers. Gasket and adhesive are adopted to seal as best as possible all the air leakage paths. This is certainly an agreeable approach, being the ventilation one of the major factor influencing the mass exchange[1] between the indoor and outdoor environment. However, it has been demonstrated that the most influencing phenomenon in case of museum showcases is , frequently, represented by gas diffusion.

The adoption of the "*air change rate*" word and concept, n [1/h], as a performance parameter, does not certainly help in clarifying the real physical mechanism that takes place and can lead to misunderstandings among the persons involved in the museum works. The reason of this lays in the typical assumptions that are done solving the generic mass balance equation of a pollutant (or water vapor or tracer gas) for a building (sector from which these concepts have been derived). In the built environment, in fact, the contribution of diffusive phenomena to the mass exchange rate is negligible compared to the effect of ventilation (convective transport). The continuity equation of a generic pollutant or gas (assuming constant and uniform density over the volume and no endogenous pollutants production) for a typical room can be written as [6, 7]:

$$\sum_{in} Q_{in} \cdot C_b - \sum_{out} Q_{out} \cdot C_{out} = \frac{\partial \left(V \cdot \langle C \rangle \right)}{\partial \tau} \qquad (1)$$

[1] In case of RH control, the mass balance of water vapor is of interest.

Introducing the ventilation efficiency, $\varepsilon_v = \dfrac{C_{out} - C_b}{\langle C \rangle - C_b}$, assuming steady-state air flow rate (so that $\sum_{in} Q_{in} = \sum_{out} Q_{out}$) and perfect mixing (ε_v=1), the solution of equation (1) can be written as:

$$\langle C(\tau) \rangle - C_b = \left(\langle C_0 \rangle - C_b \right) \cdot e^{-n \cdot \tau} \tag{2}$$

Being $n = \dfrac{Q}{V}$ the air change rate. Therefore, in case of a typical building and/or analogous enclosed spaces, the concentration time history of a generic pollutant can be satisfactorily described through the air change rate concept, as underlined by equation (2).

However, if part of the container envelope (walls and/or floor, roof) is permeable to gaseous pollutants, as it usually happens in case of museum showcases (figure 1), the continuity equation for pollutant (the endogenous source term is again assumed equal to zero) becomes:

$$\sum_{in} Q_{in} \cdot C_b - \sum_{out} Q_{out} \cdot C_{out} + q_d = V \cdot \frac{\partial \langle C \rangle}{\partial \tau} \tag{3}$$

Neglecting the edge effects and the buffering (unsteady sorption/desorption) of the gas within the permeable material, hypothesizing a diffusion according to the Fick's first law, the q_d term may be modelled as:

$$q_d = \frac{\dot{m}_d}{\rho_{gas}} = - A \cdot D_{gas} \frac{\Delta C}{s} \tag{4}$$

Combining equation (3) and (4), under the simplifying hypotheses discussed in [8], it is possible to write:

$$-\left(\langle C \rangle - C_b \right) \cdot n - \frac{A \cdot D_{gas} \cdot \left(\langle C \rangle - C_b \right)}{V \cdot s} = \frac{d\left(\langle C \rangle - C_b \right)}{d\tau} \tag{5}$$

Integrating equation (5) under the same assumptions adopted for equation (1), one obtains:

$$\left(\langle C_{gas}(\tau) \rangle - C_b \right) = \left(\langle C_{gas,0} \rangle - C_b \right) \cdot e^{-\left(n + \frac{A \cdot D_{gas}}{V \cdot s} \right) \cdot \tau} = \left(\langle C_{gas,0} \rangle - C_b \right) \cdot e^{-\alpha \cdot \tau} \tag{6}$$

By comparing equation (2) and (6) it is possible to see that the effect of the diffusive transport of the pollutant determines an increment to the value of the air change rate, n.

In these conditions the exponent of the concentration decay curve (equations 6 and 7) cannot be called the "air change rate", being:

$$\alpha = n + \left(\frac{A \cdot D_{tracer}}{V \cdot s} \right) = \frac{Q}{V} + \left(\frac{\delta_{tracer} \cdot A \cdot p_{atm}}{V \cdot s \cdot \rho_{tracer}} \right) \qquad (7)$$

The concentration time history of pollutants becomes a function of α and not only of the air change rate, n=$\frac{Q}{V}$.

The difference between these two quantities increases when:

- the gas diffusion coefficient D_{gas} increases, or, better, when decreases the gas diffusion resistance of the envelope (defined as $\frac{s}{D_{gas}}$);
- increases the area of the gas permeable surface, A;
- the ratio A/V is high (this condition is likely to happen in case of small containers);
- the ventilation air flow rate is low (in this case the magnitude of n will be comparable or smaller than the term $\frac{A}{V} \cdot \left(\frac{s}{D_{tracer}} \right)^{-1}$, a situation typical in museum showcases).

To avoid a possible misunderstanding in the following sections the quantity α will be addressed as the "equivalent air change rate".

Performance assessment of the museum showcases

Two features need to be addressed in order to fully characterize the ability of the showcase envelope in keeping the indoor environment controlled: one is the air tightness, which exerts its influence on the ventilation[2], the other is the gas permeability, which drives the diffusion.

[2] For a given showcase, the air flow rate due to ventilation depends on the air velocity near the envelope, originated by air movements on the outside facing surface of the container, and on the temperature difference between the indoor/outdoor of the showcase.

An experimental test based on pressurization techniques can be adopted to assess the air tightness [6]. Instead, for quantifying the simultaneous effect of ventilation and gas diffusion, that is, the overall phenomenon describing the pollutant exchange between the micro and macro environment, a tracer decay technique demonstrated to be a suitable approach (see e.g. [8] for a theoretical background).

In order to verify the proposed testing procedures, and to analyze the relative influence of ventilation and diffusion on the RH control in museum showcases, an experimental campaign has been developed in the laboratory.

Three different types of box shaped experimental museum containers (internal size: 0.58 x 0.19 x 0.38 m and volume: 0.042 m^3), with different air tightness and gas permeability values, have been built and analyzed. Measurements were performed both with and without buffer materials (ArtSorb®) inside the showcases.

In particular, the features of the three studied showcases were:

- *SI showcase (air and gas tight)*: completely made of Plexiglas, virtually perfect air and gas tightness;
- *VI showcase (gas tight)*: completely made of Plexiglas, with calibrated airy holes (diameter 5 mm). The holes (maximum 10 in total) can be opened or closed on demand. In the experiments here described 2+2 holes were opened (2 openings on the lower part of a vertical wall, 2 holes on the upper part of the same wall) (symbol: *VI2*);
- *SP showcase (air tight)*: five walls are made of Plexiglas, one wall made of MDF (Medium Density Fiber Board – MDF has a quite high air tightness and gas permeability, [8]).

For each container a preliminary characterization of the envelope has been done by performing both pressurization tests (with positive and negative pressure differences) and tracer decay experiments (figure 2 shows a scheme of the laboratory apparatuses). These campaign allowed to classify the showcases performance and to verify the capability, drawbacks and advantages of the proposed measurements techniques.

The pressurization tests provided the values of C, air permeability of the showcase (the flow exponent was always assumed equal to 0.67 for the assessment of C) and the tracer gas measurements provided the equivalent air change rate, α. Results are resumed in table 1. Examples of pressurization test and tracer decay measurement results are also shown in figures 3 and 4, for an actual museum showcase (test were performed in the field).

On a subsequent phase of the research, the influence of the showcase envelope features on the RH control was analyzed. To this aim, a series of relative humidity response tests have been performed inside a climatic room (climatic room size: 5.05 m × 2.90 m × 2.65 m).

In particular, each container has been subject to a sinusoidal variation of RH (with different periods - 24, 48 or 72 hours - and same amplitude - RH fluctuations between 40 and 70%) at a constant air temperature ($T \approx 25$°C). Temperature and relative humidity inside and outside the showcases were continuously monitored by means of a Delta-T Devices DL3000 datalogger (sampling rate: 5 min). Tests were repeated with and without buffer materials inside the showcases.

Figure 5 shows, as an example, the relative humidity versus time for the showcases without buffer materials (period of the sinusoidal variation of RH: 24 hours). Time profiles of RH inside the various showcases with 400 g of buffer materials are shown in figures 6 and 7, for a period of 24 and 72 hours respectively.

Finally, studies on real showcases equipped with buffer materials and operating under actual museum conditions were carried out by monitoring for medium/long time the indoor/outdoor environmental parameters (T and RH. Measurements were performed using Smartreader SR002 and/or Testo 175-H2 microdataloggers).

Results and Discussion

As expected, the performance of the showcase envelope exerts a large influence on the control of the internal relative humidity. A good, air and gas tight, container (like *VI*) allows to decouple the indoor environment from the fluctuations of the outdoor parameters (fig. 5). The influence of the air tightness and of the gas permeability of wall materials on the RH stabilization revealed to be of the same order of magnitude. In terms of amplitude of RH variations, an almost perfectly airtight, but poorly gas tight system (e.g. container *SP*) behave like an air leaky box (e.g. container *VI2*). However, as shown in figure 5, thank to the relatively larger buffer effect of the gas permeable material, the oscillations of RH for the *VP* box are delayed compared to the outdoor variations (i.e. in the climatic room); for the air leaky systems (*VI2*) the two curves are, instead, almost in phase.

As far as the tests with the showcases equipped with buffer materials (ArtSorb ® casset with 400g of beads, pre-conditioned at an RH of 55%) are concerned, figure 6 and 7 shows, as an example, the results of two tests.

For the high performance showcase (*VI*) the buffer materials does not add any detectable benefit, being the envelope alone already able to keep the relative humidity inside the box stable and non influenced by the outdoor variations. Nevertheless, the presence of the Artsor® preconditioned at 55 % allows to modify, in an almost permanent way, the internal value of RH (keeping it at a different value compared to the outdoors. See e.g. fig. 5 and 6 & 7). As far as the *SP* and *VI2* showcases are concerned, instead, the introduction of the buffer material, as expected, produces an improvement in terms of fluctuations smoothening. It has, however, to be observed that the same mass of buffer materials resulted in a different effect if applied to the *VI2* box and the *VP* box. In the first case the smoothening is larger and it seems to be only marginally influenced by the period (24 or 72 hours) of the outdoor fluctuation of the RH (see fig. 6 and 7). In the latter case, the buffer material can still dampen the amplitude of the outdoor fluctuations (even if less effectively), but the performance is largely influenced by the period of the outdoor fluctuations. Longer periods determine a smaller ability of the Artsorb® in keeping controlled the indoor RH (daily gradient of RH: about 5%).

Finally, in figure 8 the time profiles of the air temperature inside the climatic room and the three experimental showcases are plotted. The variations of temperature are very small (due to the tolerance of the control system of the climatic room. The tests were, in fact, done at a nominally constant temperature), but the thermal inertia of the container introduces some delays between the outdoors and the indoors[3]. These small temperature differences (less than 0.5 °C) are the major responsible of the natural ventilation of the showcases (test were done in practically still air).

Finally, in order to verify the findings of the laboratory measurement campaign, an investigation on a series of actual museum showcases (at the "Museo Nazionale del Cinema" di Torino – Italy) was performed. In particular, the effectiveness of the passive control of RH by means of buffer materials was investigated by comparing the

[3] SI and VI2 boxes, all made in Plexiglas, showed a comparable trend. The larger thermal inertia of the MDF board (VP) allowed a larger delay of the temperature profile (fig. 8).

performance of “old” and “new”, retrofitted, showcases (whose features are summarized in Table 2). The retrofit always consisted in interventions aimed at improving, to a lesser or larger extent, the overall tightness of the container. Figures from 9 to 14 resume the results of these activity and stress, once again, the conclusions drawn from the laboratory studies.

Conclusions

For a reliable and effective control of the relative humidity inside museum showcases the container envelope has to provide satisfactory performance in terms of tightness. This tightness, as highlighted, must refer to both air tightness and gas tightness. In fact, it has been demonstrated that for typical museum showcases, ventilation and diffusion play an equivalent role in determining the water vapour exchange between the indoors and outdoors of the enclosure.

To assess the overall performance of the container, a tracer decay procedure has revealed to be the most suitable test. Pressurization techniques can only address the quality of the showcases in terms of air tightness (that is, to certify the care with which joints and connections are made), but does not supply any comprehensive information about the ability of the container in preventing unwanted variations of the internal relative humidity due to the variations in the outdoor environment.

A series of measurements performed in the field, on real museum showcases, has confirmed the findings achieved in the laboratory.

Symbols

A = panel area [m^2]

α = equivalent air change rate (exponent of the tracer gas decay curve) [1/s] or [1/h] or [1/day]

C_{out} = volume concentration at the outlets [ppm]

C_b = background concentration [ppm]

<C> = room mean concentration [ppm]

C = concentration [ppm]

C = air permeability [l/(h·Pa$^{0.67}$)]

$$C = \frac{Q}{\Delta p^{0.67}}$$

D_{gas} = gas diffusion coefficient [m^2/s]

δ_{gas} = gas permeability coefficient [kg/(smPa)]

ε_v = ventilation efficiency [-]

$\dot{m}_d$ = mass flow rate [kg/s]

n = air changes [1/s] or [1/h] or [1/day]

n = flow exponent of the curve

$$Q = C \cdot \Delta p^n$$

p = pressure [Pa]

Q = ventilation air flow rate [m^3/s]

q_d = gas volume flow rate[m^3/s]

ρ = density [kg/m^3]

s = wall thickness [m]

τ = time [s]

V = volume of the confined space [m^3]

Subscripts

atm = atmospheric

in = inlet

out = outlet

gas = pollutant, water vapour or tracer gas

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Table 1 - Pressurization tests and tracer gas measurements results (these values are an average of different repeated tests).

Showcase	Pressurization tests		Tracer gas measurements
	ΔP +	ΔP -	
	C [l/(h · $Pa^{0.67}$)]		n [1/day]
SI	Virtually ∞	Virtually ∞	0,008
VI2	219,4	228,2	1,86
SP	1,7	1,7	18,16

Table 2 "Museo Nazionale del Cinema – Torino", tested showcases' features.

Showcase	Dimension	Construction materials	Buffer materials
Old showcase (no longer in use)	0.56m× 0.56m× 0.51m Volume: 0.16 m^3	Plexiglas, MDF, poor airtight joints.	1 box of 400 g of Art Sorb. Pre-conditioned at 55%
New showcase	0.7m× 0.56m× 0.56m Volume: 0.22 m^3	Plexiglas, steel, aluminium alloy, airtight joints.	1 box of 400 g of Art Sorb. Pre-conditioned at 45%
Poster Frame	0.8m× 1.2m× 0.07m Volume: 0.07 m^3	Plexiglas, MDF	1 sheet of 160 g of Art Sorb. Pre-conditioned at 50%
Poster Frame Optimized	0.8m× 1.2m× 0.07m Volume: 0.07 m^3	Plexiglas, MDF, back side with a water vapour barrier (PE sheet)	1 sheet of 160 g of Art Sorb. Pre-conditioned at 50%

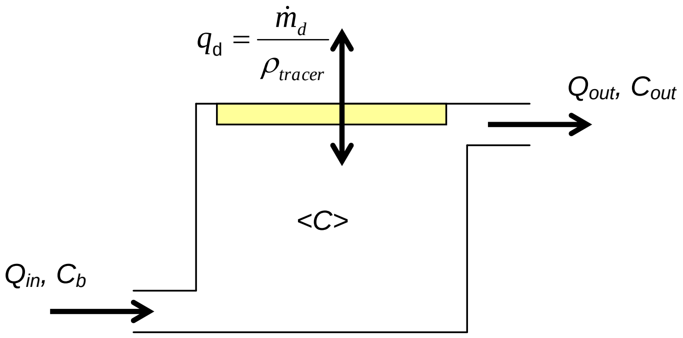

Fig. 1 - Envelope not perfectly tight to the pollutants. Fluid dynamic scheme.

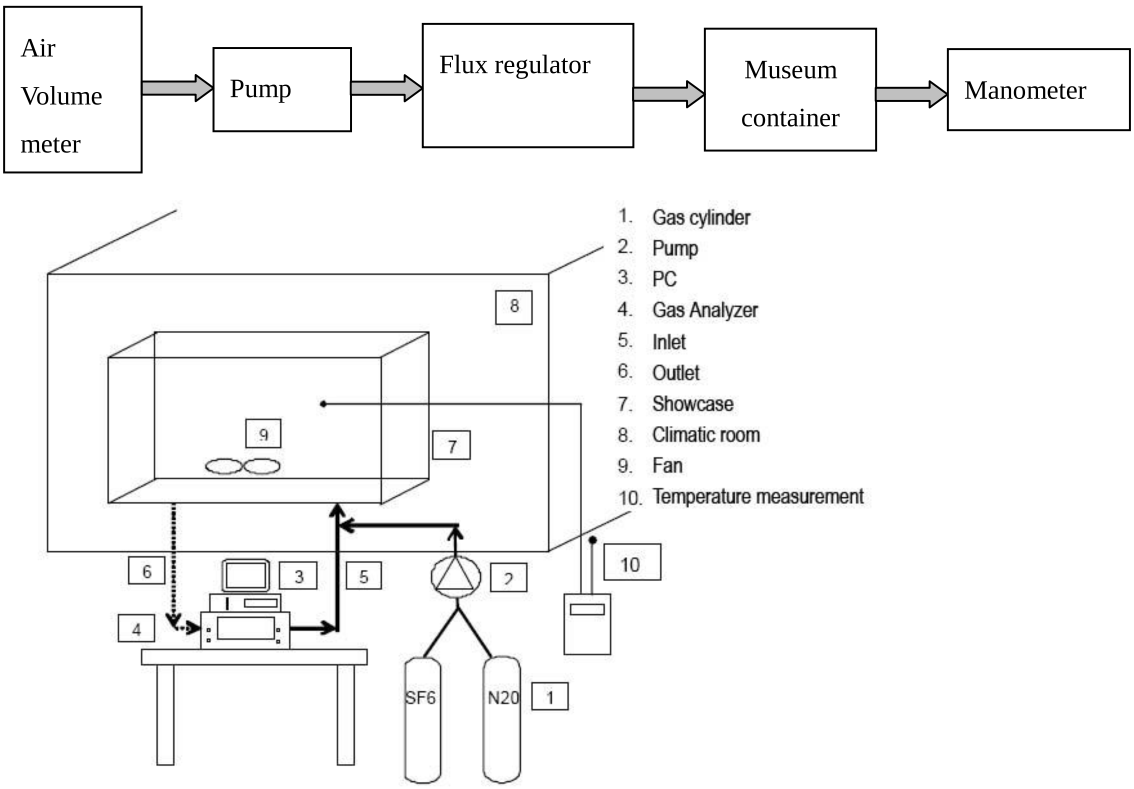

Fig. 2 - Scheme of the laboratory apparatuses used for the showcase characterization (pressurization tests and tracer decay measurements).

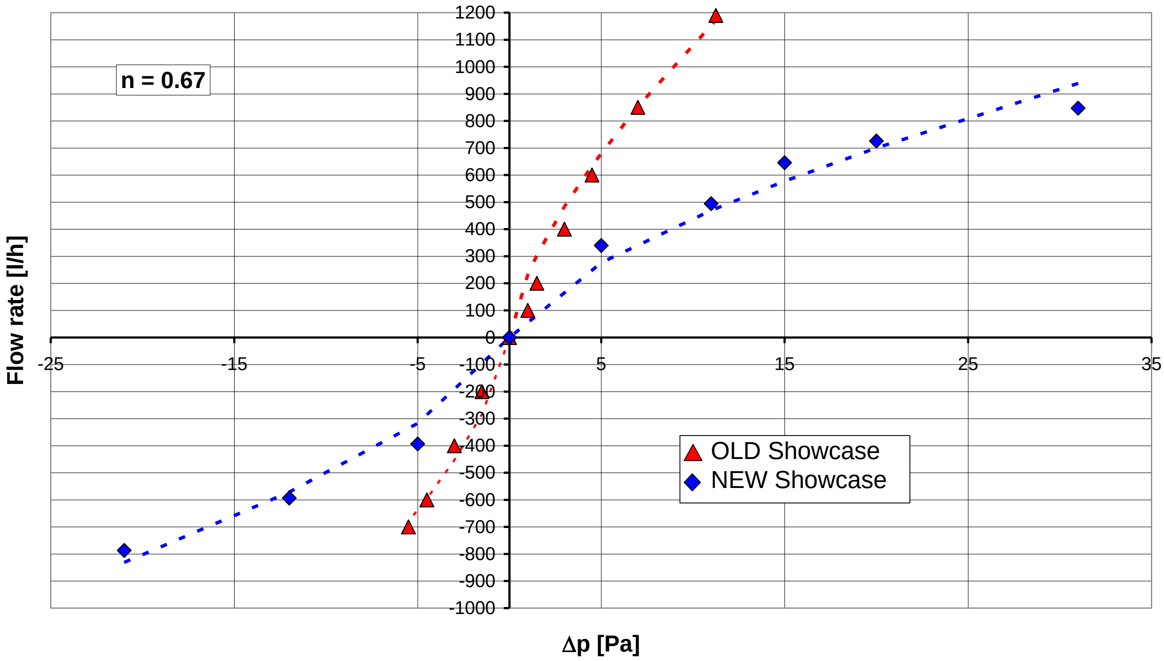

Fig. 3 - Pressurization tests – Actual showcase. Comparison between OLD and NEW Showcases (Δp^{+}: C_{old} = 231 l/($hPa^{0.67}$); C_{new} = 94 l/($hPa^{0.67}$) - Δp^{+}: C_{old} = 216 l/($hPa^{0.67}$); C_{new} = 109 l/($hPa^{0.67}$)) .

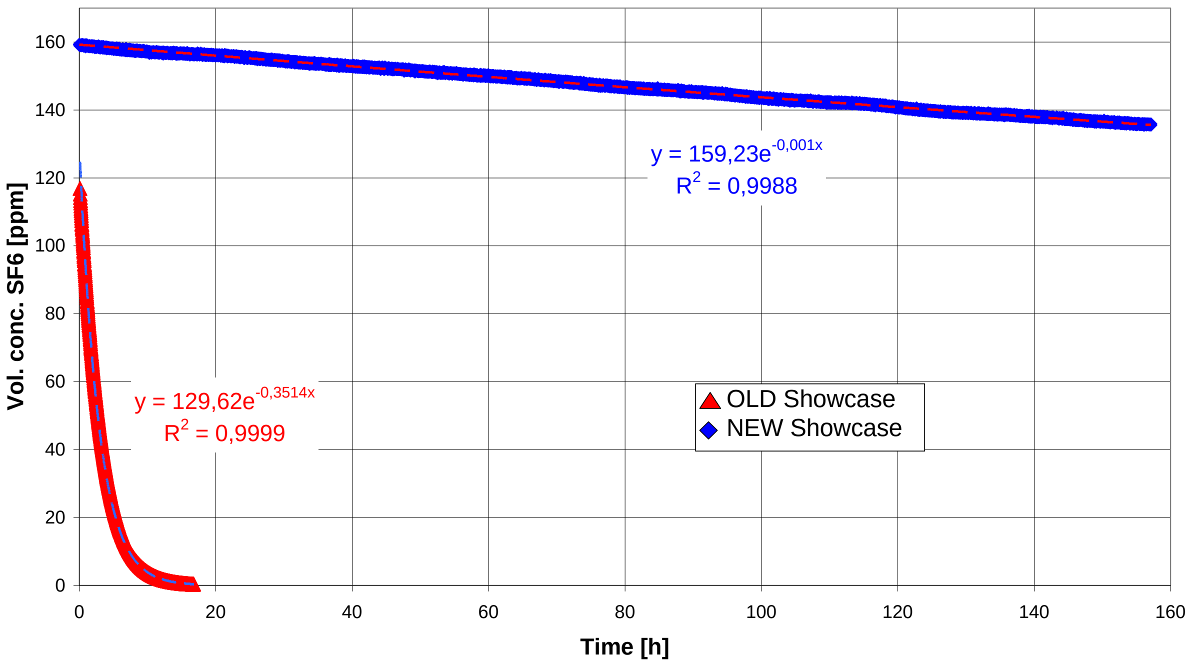

Fig. 4 Gas trace measurements – Actual showcase. Comparison between OLD (α: 8,24 1/day) and NEW (α: 0,02 1/day) showcases results.

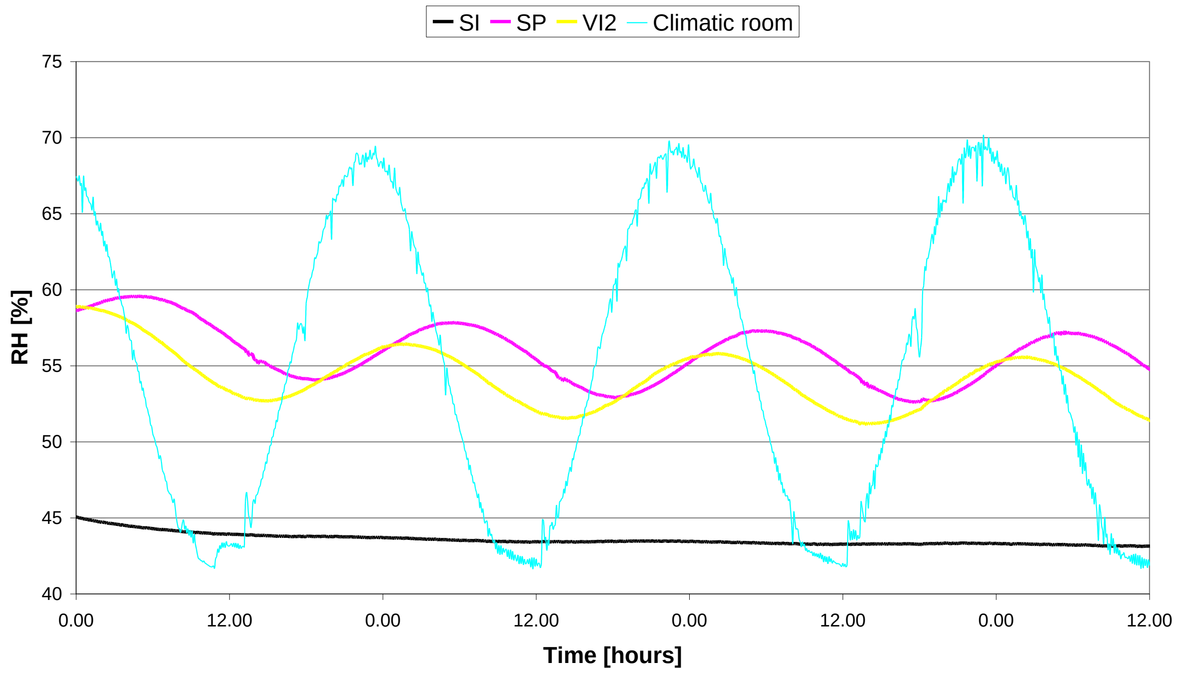

Fig. 5 - Relative humidity vs. time inside climatic room and inside the three tested showcases without buffer materials. RH fluctuations between 40 and 70% - 24 hours period.

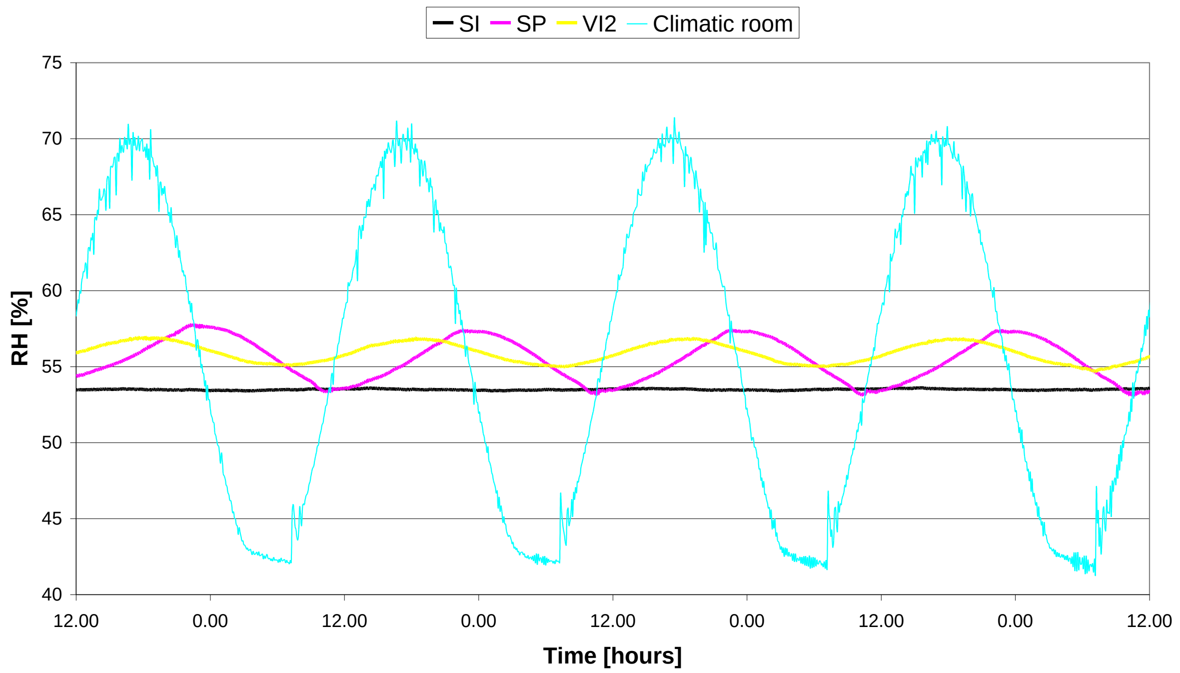

Fig. 6 - Relative humidity vs. time inside climatic room and inside the three tested showcases equipped with 400 g of ArtSorb®. RH fluctuations between 40 and 70% - 24 hours period.

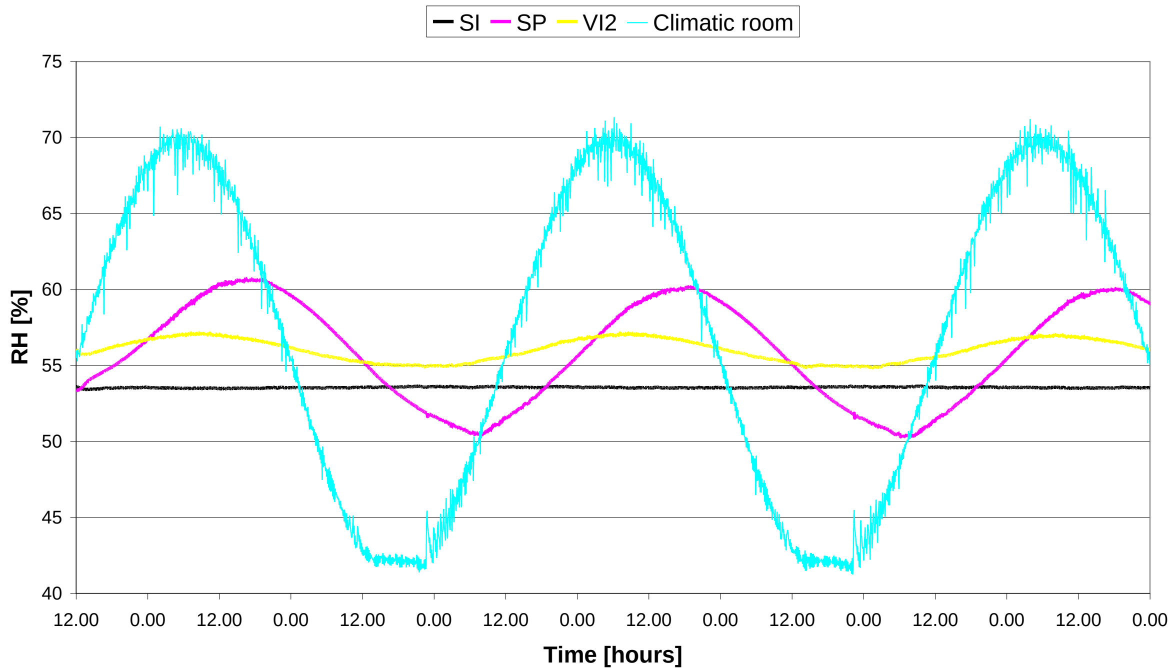

Fig. 7 - Relative humidity vs. time inside climatic room and inside the three tested showcases equipped with 400 g of ArtSorb®. RH fluctuations between 40 and 70% - 72 hours period.

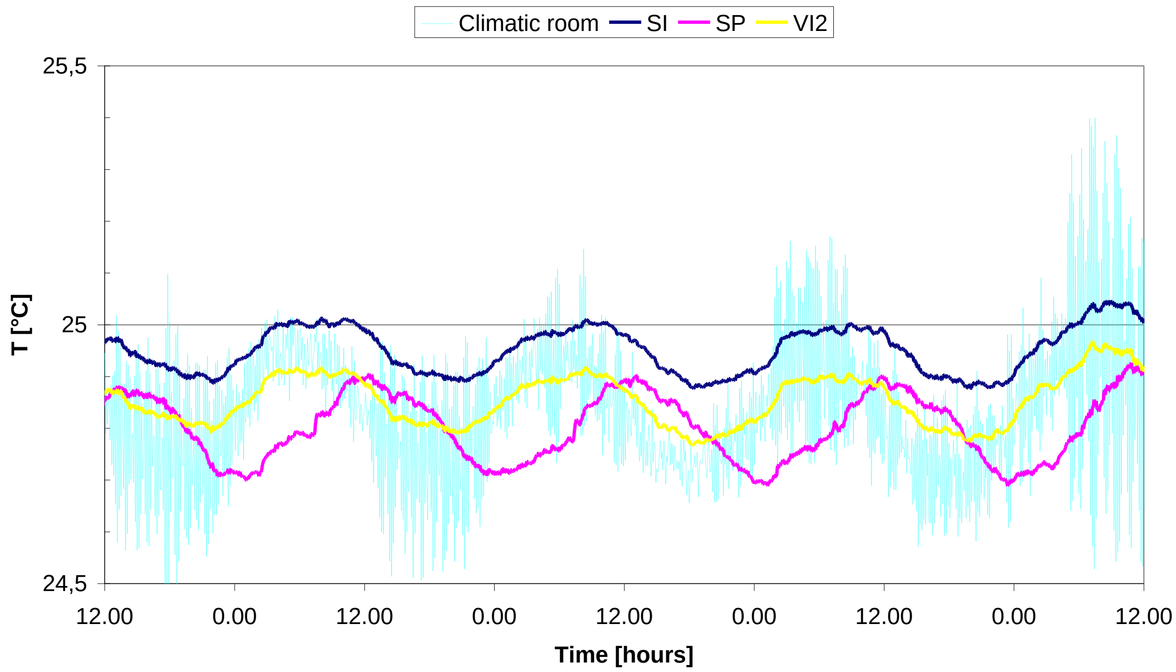

Fig. 8 - Temperature values inside climatic room and inside the three tested showcases.

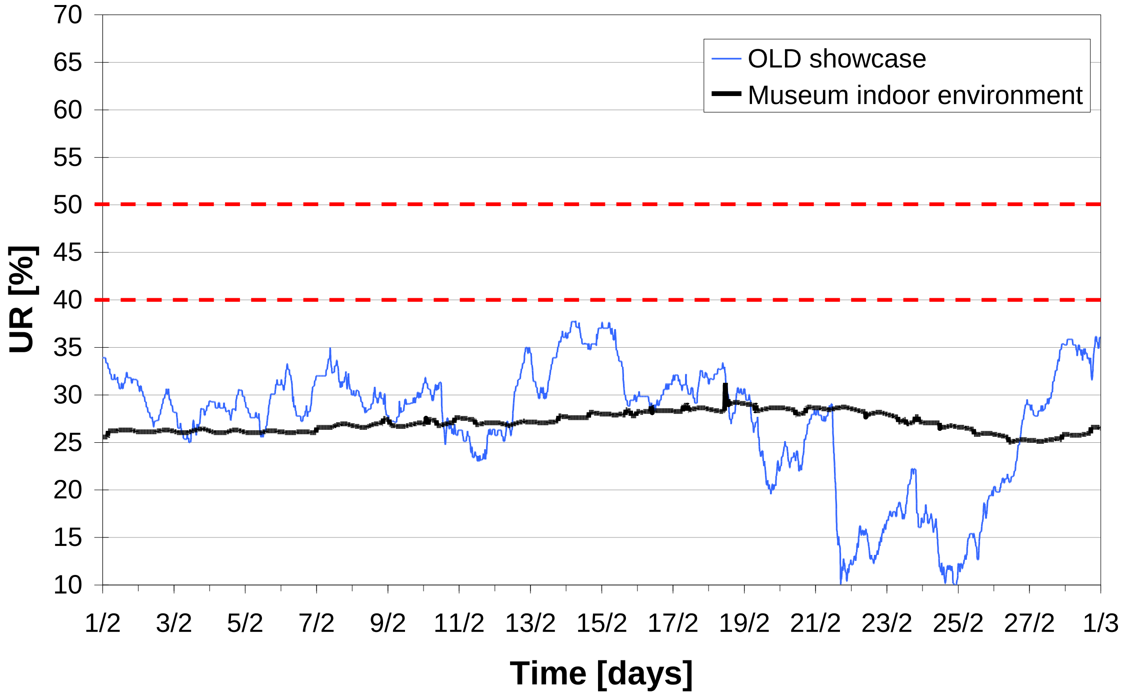

Fig. 9 - OLD Showcase; RH time profile in winter season (February). In red the acceptability interval for conservation.

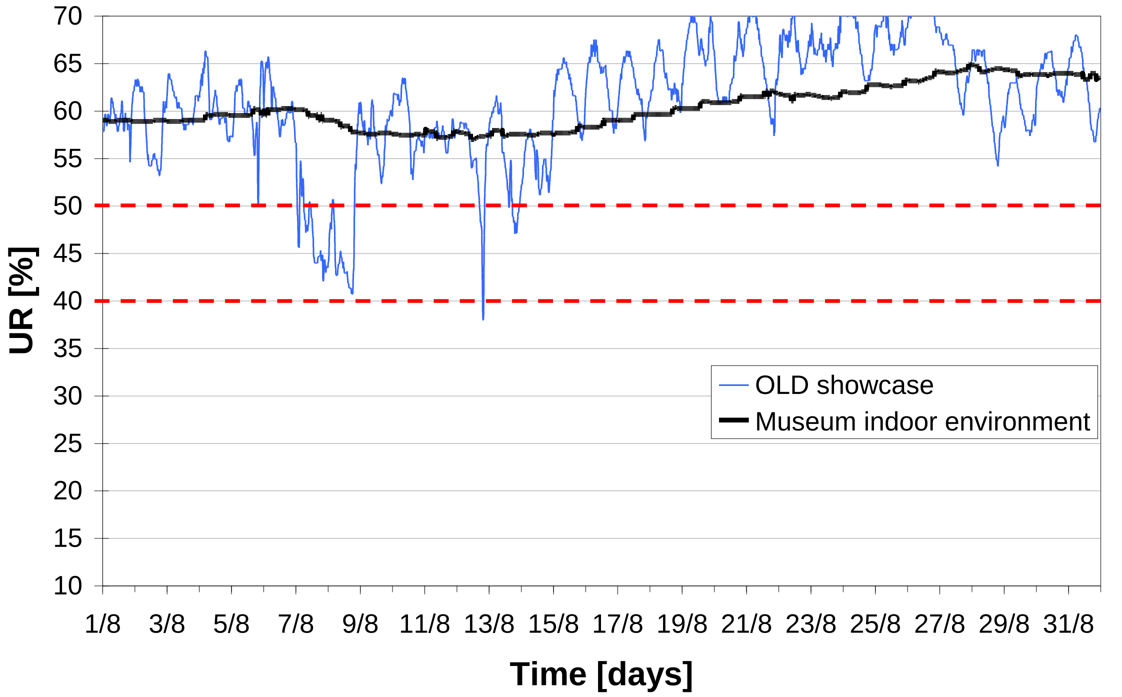

Fig. 10 - OLD Showcase; RH time profile in summer season (August). In red the acceptability interval for conservation.

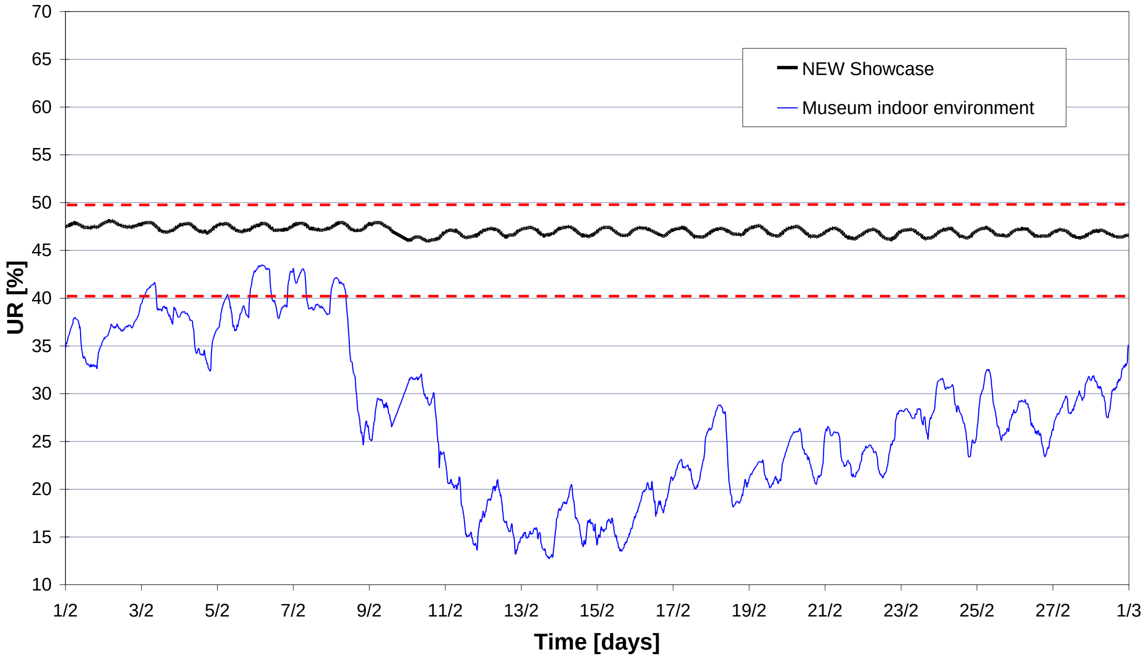

Fig. 11 - NEW Showcase; RH time profile in winter season (February). Acceptability interval for conservation.

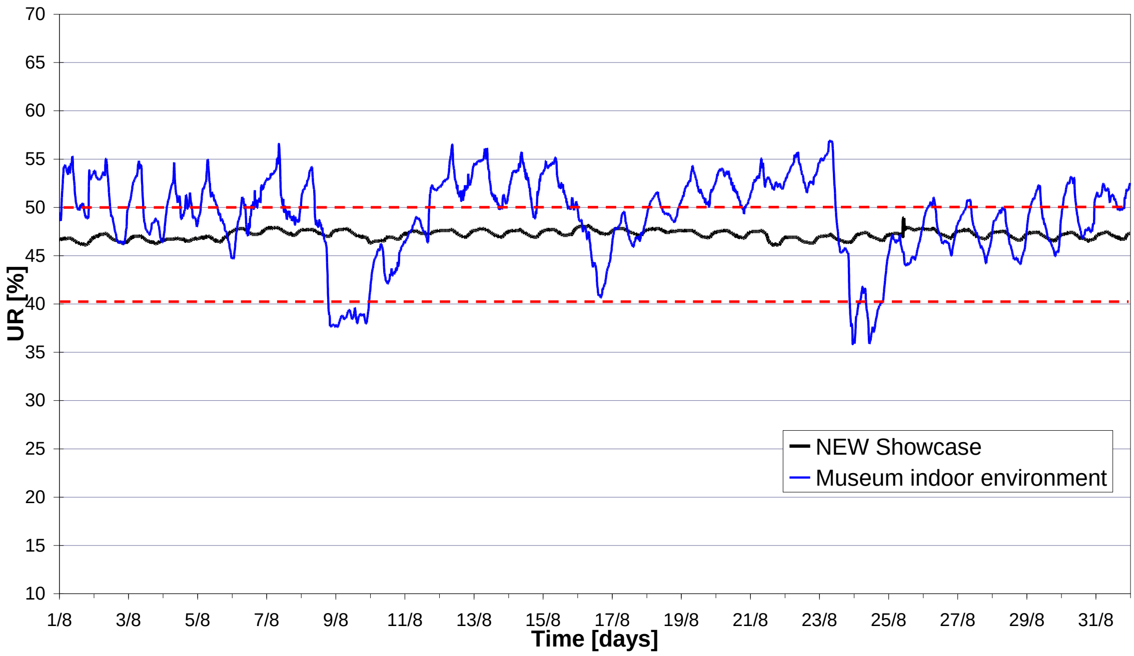

Fig. 12 - NEW Showcase; RH time profile in summer season (August). In red the acceptability interval for conservation.

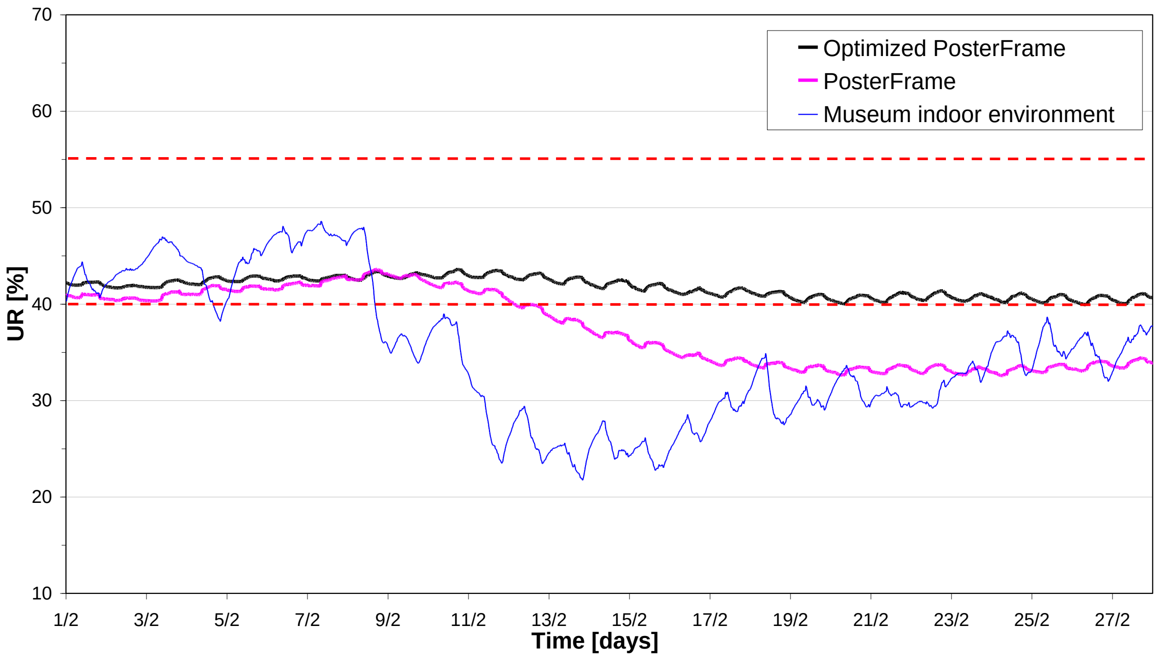

Fig. 13 - Poster Frame; RH time profile in winter season (February). In red the acceptability interval for conservation.

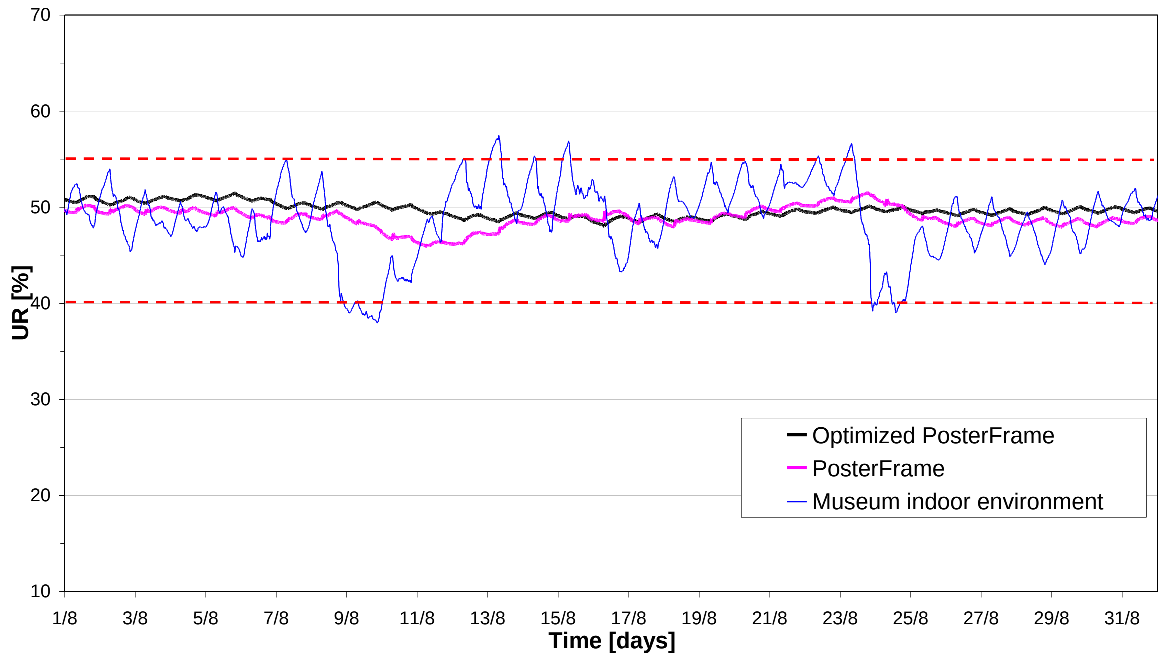

Fig. 14 - Poster Frame; RH time profile in summer season (August). In red the acceptability interval for conservation.