Passive control of temperature and relative humidity in museum showcases: the case study of the Leonardo Self-portrait

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SUMMARY
This paper deals with the design and testing of a showcase specifically built to host the Leonardo Self-portrait during a temporary exhibition. The combined effect of gas diffusion, ventilation and temperature variations on the showcase microenvironment are discussed and analyzed, with specific emphasis on the passive control of RH by means of buffer materials. The laboratory measurements, performed on this showcase to analyse the influence of various design and operative parameters, are also discussed. The laboratory results are then compared against field measurement results.

KEYWORDS
Museum environment, RH buffering, showcase performance, showcase test, preservation.

1 INTRODUCTION
Museum showcases represent a very peculiar confined space were ventilation and indoor climate conditions play an important role. Conservation of works of art, in fact, typically requires a control of the environmental parameters with a tolerance far tighter than that needed to assure comfort of people. In this paper an example of a tough challenge in conservation field is described and analyzed: the case of Leonardo da Vinci self-portrait temporary exhibition from November 2011 to January 2012 at the Reggia di Venaria (Turin – Italy). It is the first time in recent years that the Self-portrait, with 12 other drawings of Leonardo da Vinci (and the famous Codex on the flights of birds), is shown outside the Royal Library of Turin. The self-portrait is not generally viewable by the public because of its fragility and critical conservation conditions. The Leonardo Self-portrait is a small drawing (about 33 x 21 cm) in red chalk (sanguine) on paper. It dates back to the later years of Leonardo’s life, presumably about 1515. After Leonardo’s death in 1519, this drawing disappeared many times, until it was sold to Carlo Alberto di Savoia in 1839. From this date on it is housed at the Royal Library in Turin. For a long period, in the past, the storage conditions were not optimal and determined different kind of degradations. In particular the Self-portrait is affected by the foxing phenomenon, reddish-brown spot and stain on paper. The causes of foxing are not well understood; one theory asserts that foxing is caused by the effect of the oxidation of iron and other substances in the paper. Probably multiple factors are involved, but scientists agree that relative humidity and temperature play a rule of remarkable importance. Because of the critical issues about the conservation, and the risk of promoting the development of the “foxing”, the temporary exhibition of the object has been authorized only under the restriction of assuring a rigorously stable and controlled environment1.

The acceptable ranges for relative humidity and air temperature were set, respectively, to: 50 % < RH < 60 % and 17 °C < T < 20 °C. Since it is virtually impossible to assure such tight limits under all boundary conditions and circumstances2, even if the room is equipped

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1 Lighting, not considered in this paper for the sake of brevity, was also of concern. A limit of 50 lx to the illuminance was adopted.
2 An unpredictable, but possible, fault of the HVAC system would determine rapid and wide variations of climate conditions and would result in high risks for the preservation of the object.
with mechanical air conditioners, a double level control has been adopted. The first, coarser, environmental control is exerted through the action of an HVAC system that regulates both temperature and relative humidity in the exhibition hall (the macro-environment). The second, and finer, control is done by means of a purposely developed showcase, which is able to provide a precise tuning of the relative humidity and a backup in the event of a fault of the room air conditioning. In order to achieve a high degree of safety, it has been decided to avoid the use of active (mechanical) systems for the environment control inside the showcase and, in spite, a passive buffering of the RH (which assures a “fail-safe” behaviour) has been implemented. The compromise of this choice is represented by the fact that the temperature needs to be, almost fully, managed through the HVAC system of the room (because the showcase has a small thermal inertia).

In museum showcases the aim is, usually\(^3\), to reduce as much as possible the heat and mass exchange with the outdoor environment (that is the environment in the exhibition room), specially when stable climate conditions are provided by means of passive systems (Padfield, 1967). Accordingly to this principle, the proposed “climabox” is made of five metallic surfaces, with thermo-hardening epoxy powder finishing, and an extra-clear laminated glass (figure 1). All the joints between the metallic components are welded and sealed and all the moveable parts are provide with neoprene gaskets. The aim was to achieve a high degree of air/gas tightness (minimum design requirement: air changes per day \(\leq 0.1\)). The RH buffering is done introducing inside two lateral volumes of the showcase about 1 kg of Pro-sorb\(^\circ\), properly preconditioned. Besides, the climabox is equipped with wireless sensors to continuously monitor the internal relative humidity and temperature. Both the buffer material and the measuring equipment can be accessed separately and independently form the self-portrait, to simplify maintenance and to improve the safety.

After the construction, the showcase has been the subject of a testing campaign aimed at experimentally verifying its performances. In particular, the following investigations were carried out in the laboratory before the exhibition: air/gas tightness measurements, by means of a tracer gas technique, stress tests to verify the thermo hygrometric response of the showcase to wide and sudden variations of the external air temperature and relative humidity. Moreover, during the exhibition, a continuous monitoring of the indoor environmental parameters has been done and the Conservation Risk Index (CRI) has been assessed.

2 METHOD AND EXPERIMENTAL CAMPAIGN

The aim of the experimental campaign was to verify the performance of the showcase in terms of internal relative humidity control and capacity of “peak-shaving” the fast variations of the external air temperature. Preliminarily to the measurements, all the adopted equipments and sensors were calibrated and/or verified; the obtained measurement accuracies are: \(\pm 0.3^\circ\mathrm{C}\) for \(T\), \(\pm 3\%\) for RH. The accuracy of the wireless monitoring system was also checked; it resulted to be within the nominal intervals declared by the manufacturer (furthermore, suitable correction curves were determined for improving its accuracy).

\(^3\) Attention has to be paid to materials which could release contaminant (outgasing). In such case it is preferable to design a showcases with a suitable air ventilation rate able to remove the self produced pollutants.
Since it is well known that the “tightness” of the envelope plays a fundamental role in determining the performance of a showcase and in allowing an effective use of the buffer materials (Weintraub, 1981), the air/gas tightness of the showcase was measured through a tracer decay procedure during the first phase of the study (SF₆ was used as tracer gas). In relation to this feature it is worth noting that a wrong, but common, belief among some museum curators is that air exchange between the showcase and the room (i.e. ventilation or convective transport) is the most relevant feature as far as the passive RH control is concerned. Consequently the “air change rate” concept is usually adopted and great care is paid by manufacturers in building well “sealed” containers (using gasket and adhesive to close all the air leakage paths). This is certainly an agreeable approach, being the convective transport one of the factor influencing the mass exchange between the indoor and outdoor environment; however, it has been demonstrated (Filippi & Perino, 2007) that, frequently, ventilation is not the most influencing phenomenon in case of museum showcases, being gas diffusion predominant. The adoption of the words “air change rate” and their related concept, $n \ [1/h]$, does not certainly help in clarifying the real physical mechanism that takes place in the showcase and can lead to misunderstandings. To avoid such possible confusion, in the present paper, the term “equivalent air change rate” (which cumulatively accounts for air and gas tightness - Perino & Bonvicini, 2010), $\alpha \ [1/day]$, will be used instead. In fact, the decay curve of the concentration, measured during a tracer gas measurement (which is typically named “air change rate”), actually includes not only the effect of ventilation (i.e. air tightness), but also the diffusive phenomena, that is the gas/vapour exchange between the indoor/outdoor of the showcase due to the gas permeability of materials (i.e. gas tightness).

In order to improve the accuracy of the estimate, the value of the equivalent air change rate, $\alpha$, was assessed by means of the “moments of concentration” method⁴. Measurements were done inside a controlled environment at a constant temperature of 20 °C (figure 2). In the second phase of the activity, a series of stress tests were performed by varying the external relative humidity and air temperature. The showcase, equipped with two boxes (500 g each) of Pro-Sorb® preconditioned at a relative humidity of 55 %, was introduced inside a thermostatic chamber. The environment inside the test room was kept at $T = 26 \ ^\circ C$ and RH = 30 % for three days and then suddenly moved at $T = 21 \ ^\circ C$ and RH = 70 % and kept in these conditions for another three days. Indoor and outdoor air temperature and relative humidity were continuously monitored respectively by means of wireless sensor and traditional Delta Instrument probes. Finally, during the whole exhibition period both the room and showcase environments were continuously monitored by means of an integrated wireless sensor network. This measurement apparatus is completely autonomous and allows to set-up alarm ranges for the parameters under control. In this way any unpredictable event that would cause excessive variation of relative humidity or air temperature would be immediately reported, via

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⁴ $\alpha$ can be considered, as a first approximation, as the exponent of the decay curve of the tracer concentration. Therefore it is usually assessed through a simple best fit of the measured concentration data vs time.
SMS or e-mail, to the responsible of the conservation, thus allowing a fast activation of all the preventive measures needed to restore safety conditions for the Self-portrait.

3 RESULTS AND DISCUSSION

Figure 3 shows the time profile of the SF$_6$ concentration decay. The resulting equivalent air change per day is: $\alpha = 0.07$ 1/d, about 30% better than the minimum design requirement. The achievement of such a high air/gas tightness constitutes a good basis for the possibility of optimally control the RH and pollutants inside the showcase. This expectation has been further confirmed by the stress tests, whose results, in terms of time profiles of internal and external relative humidity and air temperature, are shown in figure 4 (a) and (b), respectively. It is possible to see that excellent performance are obtained in relation to the passive control of the relative humidity, even when the showcase is subject to severe external conditions. The temperature profiles plotted in 4b highlights, instead, that the capability of the showcase in controlling the air temperature is somehow limited. Finally, the results of the continuous monitoring performed during the temporary exhibition are summarized in figure 5, where the internal and external RH (figure 5a) and air temperature (figure 5b) are plotted together with the acceptable lower and upper limits for the conservation. Moreover, the cumulative distribution functions of the same parameters are shown in figure 6. As it possible to see, the RH inside the climabox is remarkably constant and insensitive to the external conditions. Just very small changes are shown, due to the day/night cyclic variation of the temperature (they are < 1 %, and hence far lower than the accuracy of the measurement equipment). The monitored data were further analyzed accordingly to the Italian standard UNI 10829 and the conservation risk index (CRI, Filippi et al., 2006) for RH and temperature was assessed (figure 6a and 6b), CRI is 0% for the relative humidity and 1.4 % for the air temperature (that is, for 1.4 % of the time the air temperature was comprised between 16.5 °C and 17 °C).

5 DISCUSSION AND CONCLUSIONS

Results of the tracer gas measurement proved that the design and construction of the showcase was satisfactory as far as air/gas tightness are concerned. This is a fundamental pre-requisite for attempting a successful passive control of the internal environment. Moreover, the outcomes of the stress tests showed the optimal performance of the showcase in buffering the relative humidity. During the three days at very low and very high external RH, the internal value stayed constant. Only in the transient phase, when the thermostatic chamber was switched from the first to the second set-up, a variation of about 5 % is shown (red dashed circle in fig. 4a). This peak was caused by the rapid change of the temperature in the test room (that dropped from ~ 26 °C to ~ 21 °C in a period of ~ 1 h, fig. 4b). Such variation was so fast that the thermal and hygrometric equilibrium between the air inside the show case and the buffer material was no more achieved and, therefore, some time was required for the water vapour exchanges to take place and to restore the correct value of the internal RH.
This phenomenon highlights, once more, the importance of achieving a good thermal uniformity/stability inside tight showcases when buffer materials are used. Nevertheless, it has to be underlined that, from a practical point of view, this behaviour is not of concern. On one side the variation of the relative humidity is, indeed, quite small (within the requested tolerance range) and, on the other, such a rapid and severe swing of the external air temperature is not likely to happen in real exhibition rooms (even in case of a fault of the HVAC system), due to their relatively high thermal inertia.

A specific series of tests was also performed to deepen the analysis of this phenomenon. The obtained results confirmed this conclusion. These tests are not reported in the paper for the sake of brevity.
In relation to air temperature control, the climabox is only able to phase out relatively small and fast fluctuations. As it is possible to see, the oscillations due to the hysteresis of the control system of the thermostatic chamber (whose amplitude is of about 1.5 °C and period is of about 2 hours and 15 minutes – black curve of fig. 4b) are completely filtered and smoothed (red curve). However, steady and larger changes (like the one from the first part of the test to the second) are almost entirely and instantaneously transferred from the outside to the inside of the showcase. Similar behavior is shown for the real operating conditions (fig. 5b), when the temperature swing has a period of 24 h; in such case the internal and external profiles are almost identical and the showcase can just reduce the maximum peak of about 0.5–1 °C. The periodic fluctuation of the internal air temperature is clearly underlined in figure 5b; it is caused by the diurnal variation of the outdoor temperature and, above all, by the internal heat loads (mainly constituted by the visitors and the electric appliances, that are present only during the day time). Therefore, as far as the temperature control is concerned the conservation strategy has to rely primarily on the HVAC system of the exhibition room.

On the contrary, during the operational phase (exhibition), it was possible to keep the internal RH very stable, thanks to the combined effects of the envelope and buffer material. The average value of the relative humidity was about 57 % and the maximum deviation during the two analyzed months was less than 1 %. It is worth noting that in spite of a predictable decrease of the internal relative humidity due to the daily rise of the air temperature, the RH value increases. Such apparently “anomalous” behavior (in moist air the RH decreases when the temperature increases) is, in reality, absolutely predictable and is the consequence of the interactions between the hygrometric behavior of the buffer material, of the moist air and of the cardboard supporting the self-portrait. These multiple water vapor exchanges, that takes place between the three main substances in the climabox, are very important and need to be carefully considered especially during the introduction of the work of art inside the showcase. In fact, the quantity of water vapor involved in the sorption-desorption process of the paper cardboard and of the Pro-sorb®, due to the temperature disequilibrium, is order of magnitude higher than that in the moist air inside the showcase. For this reason great care and special procedures were taken during the insertion of the Self-portrait inside the showcase.

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