Passive control of microclimate in museum display cases: A lumped parameter model and experimental tests

Francesco Romano*, Luigi P.M. Colombo[1], Mirco Gaudenzi[2],
Cesare M. Joppolo[3], Luigi P. Romano[4]

Dipartimento di Energia, Politecnico di Milano, via Lambruschini 4, 20156 Milan, Italy

Received 6 September 2013
Accepted 2 October 2014
Available online 13 November 2014

1. Introduction

Damage mechanisms and preventive conservation of works of art strictly depends on environmental conditions [1] and their variations in time. Showcases are adopted as conservation tools, to enhance objects' security and to enclose them in an appropriate, stable and safe microenvironment [2,3].

Climatic control inside display cases is achieved through active or passive systems. The first type relies on equipment able to modify (by heating, cooling, humidifying, dehumidifying, filtering) the air conditions through energy and/or mass exchange. Active systems can control and stabilize the showcase internal conditions in spite of the external ones. Passive systems focus on stabilizing the internal case conditions through a suitable air-tightness and/or components able to add thermal inertia and/or vapor adsorption capacity. The choice between active and passive systems should be based on different issues, i.e. performance in getting the desired environmental conditions, reliability and failure scenarios, operation and maintenance, energy consumptions and economic cost. Every showcase is characterized by a different response to the environmental forcing, as stated by Camuffo et al. [2], their constructive features and the final effects on protection of works of art. Thus, it is very important to rely on simulation models able to forecast the correct behavior of internal conditions of a showcase depending on different forcing sources. Schijndel et al. [4] developed a model for active showcases using HAMLAB, but the work does not take into account the influence of the relative humidity, hygroscopic material and air leakages. Lony et al. [5] improved the work of Schijndel et al. by adding the influence of relative humidity. Efforts have also been done by Yu et al. [6] by means of CFD codes in which was evaluated the influence of temperature and velocity within active showcases. Steeman et al. [7] used a commercial CFD package to study the heat and mass transport in a showcase stating that direct

---

* Corresponding author. Tel.: +39 02 2399 3823; mobile: +39 333 5239269; fax: +39 02 2399 3913.

E-mail addresses: francesco.romano@polimi.it (F. Romano), luigi.colombo@polimi.it (L.P.M. Colombo), mircogaudenzi@gmail.com (M. Gaudenzi), cesare.joppolo@polimi.it (C.M. Joppolo), luigipietroromano@gmail.com (L.P. Romano).

[1] Tel.: +39 02 2399 3887; fax: +39 02 2399 3913.

[2] Tel.: +39 02 2399 3823; mobile: +39 333 5283269; fax: +39 02 2399 3913.

[3] Tel.: +39 02 2399 3856; mobile: +39 320 8393654; fax: +39 02 2399 3913.

[4] Tel.: +39 02 2399 3823; mobile: +39 380 7874297; fax: +39 02 2399 3913.

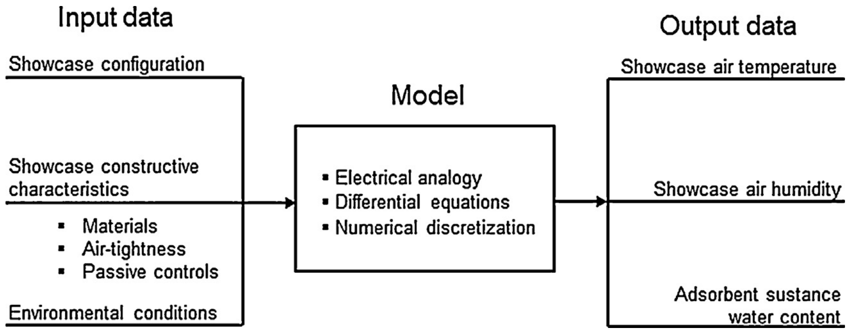

Fig. 1. Schematic structure of the simulation tool highlighting the input data, the model features and the obtainable output.

radiation on display case should be avoided as much as possible confirming previous studies [2].

Thomson [8,9] has extensively studied passive hygrometric con-trols (buffer materials). Based on his works, Brimblecombe and Ramer [10] have proposed one of the first models able to predict humidity inside a showcase of specified air exchange rate and equipped with an adsorbent material without evaluating the temperature interaction on showcase performance. More recently, Yu et al. [11] proposed another simulation model to predict relative humidity in a showcase and long-term performance of various adsorbent materials neglecting the interaction with showcases' constructive material. More in detail, none of the works previously cited evaluates the performance of a showcase in function of all the possible factors, which may cause variations of the internal microclimate conditions, thus providing a poor representation of the transient behavior. The present work is intended to widen simulation abilities by evaluating showcase performances based on the influence of the external forcing parameters such as T, RH together with constructive and internal characteristics of passive showcases materials, air leakage, and usage of hygroscopic materials such as silica gel or extra thermal capacity material such as gypsum.

The purpose of the study is to provide a reliable software tool to help the conservation specialist in:

- analyzing the existing showcase behavior;
- predicting the performance and optimizing the design of new display cases in response to forecast and/or real (acquired) behaviors of environmental conditions in the museum;
- assessing the effect of undesired and severe museum environmental influences that could affect the air temperature and/or humidity within the case with possible damage risk;
- designing a passive control system choosing a convenient (type and quantity) adsorbent material and/or additional thermal capacity to limit within acceptable ranges the environmental conditions change in the display case.

The model structure and the related assumptions have been suitably formulated to meet important requirements such as the ability in representing many different showcase types, the achievement of a good agreement between simulated and real data, simple data input and limited computing effort.

2. Simulation tool and modeling

The simulation tool, developed in MATLAB®, is composed of a Graphical User Interface (GUI) and a numerical model. Fig. 1 shows the schematic structure of the simulation tool, the input data, the model and the expected output. Input data consist of parameters about showcase configurations, thermal properties of materials, quality of construction (air-tightness), type of control system plus the internal and external environmental set of data available or desired. The output consists of internal showcase RH and T conditions, adsorbent and water content information, and air-tightness.

Concerning the modeling approach, the lumped parameters description of the showcase consists of the definition of nodal networks with interconnecting paths representing both energy and mass flows that are treated separately through dedicated networks. In both networks, each case component is represented through an electric analogous (e.g. conduction thermal resistance, convection thermal resistance, thermal capacity, vapor advective mass flow resistance, etc.); equivalent electric current generators and/or equivalent electric voltage generators are added in order to represent energy and/or mass supply. Inside the showcase, the considered heat transfer modes are limited to conduction and convection, calculated with appropriate correlations [12,13]. More-over, vapor diffusion in adsorbents is not considered since the main resistance to moisture transfer in adsorbent media is due to advec-tion [11]. The lumped parameter approach, widely adopted in the literature [4,5], has been chosen because of its ability to model the time-dependent behavior of the showcase and at the same time due to its simplicity in modeling different settings, materials and shapes. Making reference to a showcase, composed of an envelope with a capacitive wall (*i*), a non-capacitive wall (*j*) and a passive humidity control system (*ads*), typical networks for heat and mass transfer modeling are shown in Fig. 2a and b, respectively.

The thermal behavior of each component is described by a rate equation. Equation (1) models the temperature change with respect to time *t* for a capacitive component (e.g. display case's glass walls, thermal capacity for temperature control, the adsorbent substance):

$$\mathrm{C}_i \frac{\mathrm{d}T_i(t)}{\mathrm{d}t} = \frac{T_e(t) - T_i(t)}{\mathrm{R}^{ext}_{conv} + \mathrm{R}_{cond,i/2}} + \frac{T_a(t) - T_i(t)}{\mathrm{R}^{\mathrm{int}}_{conv} + \mathrm{R}_{cond,i/2}} \tag{1}$$

The energy and water balances for the buffer substance used in the passive control system take the following form:

$$\mathrm{C}_{ads} \frac{\mathrm{d}T_{ads}(t)}{\mathrm{d}t} = \mathrm{H}_{ads} \cdot \frac{\mathrm{d}W(t)}{\mathrm{d}t} - \frac{T_{ads}(t) - T_a(t)}{\mathrm{R}^{ads}_{conv}} \tag{2}$$

$$\mathrm{m}_{ads} \frac{\mathrm{d}W(t)}{\mathrm{d}t} = \frac{x_a(t) - x_{a\,ads}(t)}{\mathrm{R}_m} \tag{3}$$

Finally, the transient energy and water rate equations that hold for the air within the showcase are:

$$\mathrm{C}_a \frac{\mathrm{d}T_a(t)}{\mathrm{d}t} = \sum_j Q_j(t) + \sum_i Q_i(t) + Q_{inf} + Q^{ads}_{conv} \tag{4}$$

$$\mathrm{m}_a \frac{\mathrm{d}x_a(t)}{\mathrm{d}t} = M^{vap}_{inf}(t) - M^{ads}_{adv}(t) \tag{5}$$

All these differential equations have been discretized in time and solved using a forward difference method [14].

Fig. 3 shows the heat and vapor flows between the air inside the showcase and the external air, the adsorbent media and the

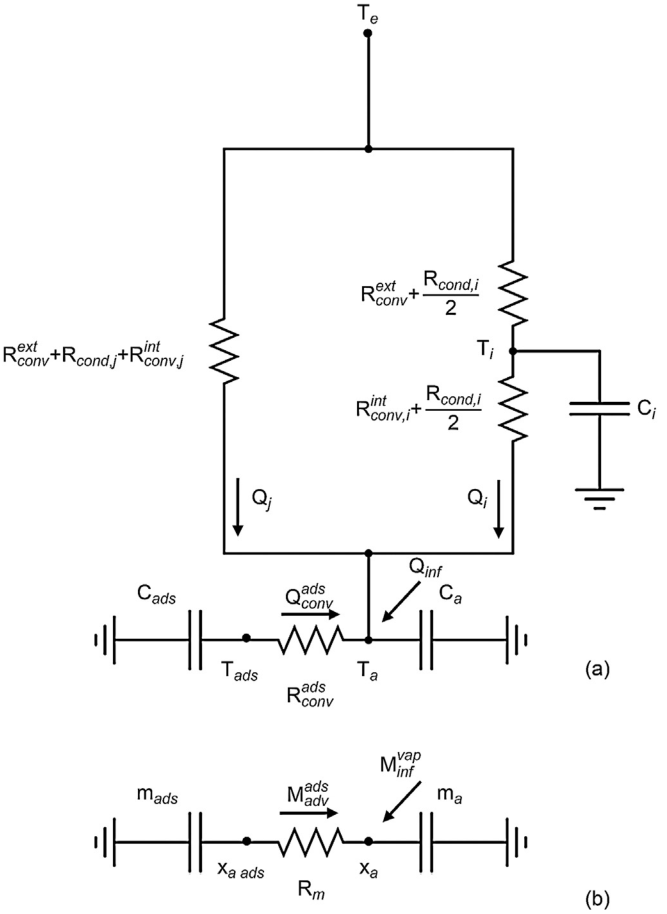

Fig. 2. Example of equivalent network of display case for the heat transfer modeling (a) and for the mass transfer modeling (b).

additional thermal capacity. Heat transfer occurs mainly through the envelope and due to temperature differences between the showcase and museum environment. A minor contribution comes from other two sources: air infiltration and adsorbent material. Museum air infiltration and water transfers between the adsorbent material and the showcase air affect moisture content within the showcase. Thus, air-tightness has a quite significant impact on display case performances. Methods are available for quantitative assessment of the air exchange rate in display enclosures [15], usually expressed in terms of air changes per hour (n).

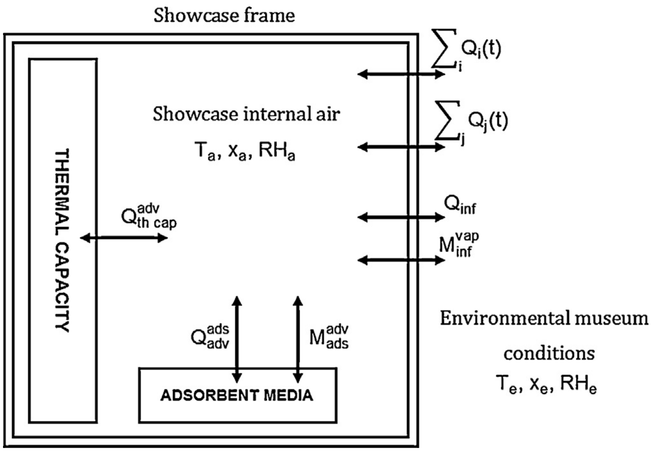

Fig. 3. Heat and vapor flows between internal air and external air, adsorbent media and thermal capacity.

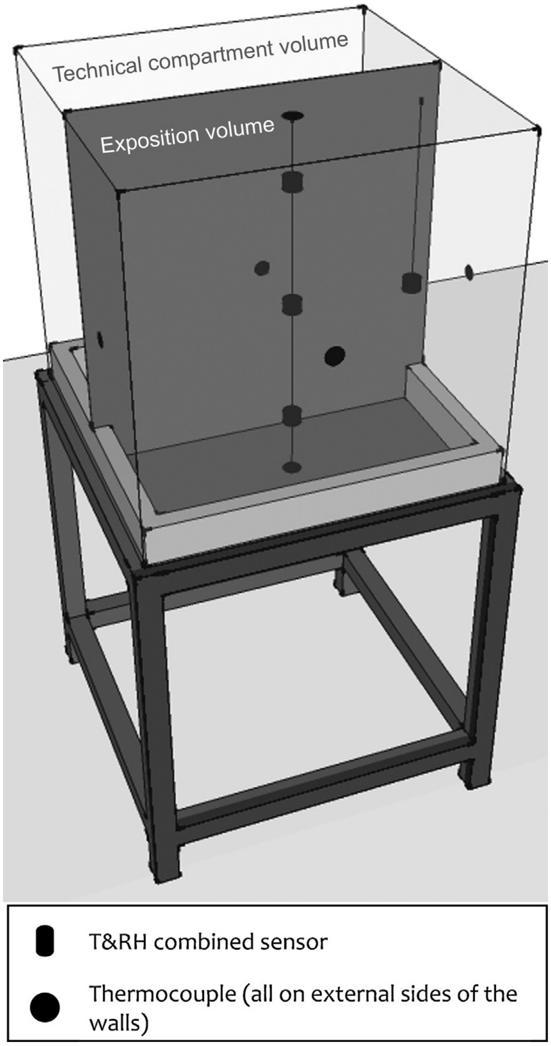

Fig. 4. Re-configurable showcase used in the experimental campaign. In the picture are also shown types and positions of applied sensors.

3. Experimental apparatus and procedures

In order to validate the simulation tool, a re-configurable free-standing showcase (internal volume 0.216 m^3) has been designed and built. The test apparatus has sidewalls and ceiling made of glass and the floor made of steel. Inside the showcase, a movable vertical steel partition allows to divide the internal volume in an exposition part and in a technical compartment. Different materials can be hosted in the technical volume to add a variable thermal and/or adsorption capacity. The re-configurable showcase permits to vary the exposition volume, the thermal capacity, the adsorption capacity and its air-tightness.

The showcase has been placed in a climatic test chamber (internal volume 28 m^3), which allows to set the environmental parameters and to impose from outside the showcase suitable changes (increase or decrease, steep or smooth) in boundary conditions (temperature and humidity).

In Fig. 4 are shown sensor types and positions. Four temperature and relative humidity combined sensors monitor the internal air and one for external conditions (uncertainty of ± 0.2 °C for temperature and ± 1% for RH). Seven thermocouples (uncertainty

Table 1
Showcase configurations.

Configuration	Description
Base case	Only glass and steel walls (with their own capacities)
Thermal capacity control	Thermal capacitive material added in the technical compartment (5 gypsum plasterboards)
Adsorption capacity control	Adsorbent substance added in the exposition volume (Artsorb® silica gel)

of ± 0.5 °C) measure the outer surface temperature of walls surrounding the exhibition volume of the showcase.

Three different showcase configurations have been used for the validation test (see Table 1). The basic configuration has been described above; the other ones are respectively obtained by adding in the technical compartment and/or in the exposition volume a thermal capacitive material or an adsorbent substance.

The capacitive material used for experimental tests is plasterboard 12.5 mm thick, with the same height and width as for the separating internal wall. In order to obtain the desired thermal capacity, five identical plasterboard panels have been assembled and put in thermal contact with the external side of the steel surface closing the exposition volume. The adsorbent material is silica gel with lithium chloride in bead type form (Artsorb®) located within the exposition volume of the showcase (146 g dry weight, 396 $\text{cm}^2 \times 0.7$ cm volume). The influence of showcase air-tightness in controlling the internal air conditions have been evaluated during the experimental campaign by varying the showcase sealing quality from a basic case air-tightness ($n = 0.008\ \text{h}^{-1}$) to both an improved one (less than $n = 0.0001\ \text{h}^{-1}$) and to a worsened one ($n = 0.017\ \text{h}^{-1}$).

4. Results and discussion

Multiple tests have been carried out varying the showcase configuration (see Table 1), its air-tightness and imposing different external conditions (T & RH) in the climatic test chamber (see Table 2).

For each test condition, the simulation model has been run in order to forecast the temperature and relative humidity inside the case. The model proposed has been validated by comparing the measured and the simulated showcase internal conditions. The relative errors calculated for each test are shown in Table 3.

The first test has been run with the showcase in basic configuraion and air-tightness ($n = 0.008\ \text{h}^{-1}$), imposing a heating transient and a subsequent thermal relaxation (test A). The showcase reacts delaying and dampening the imposed (external) temperature increase (see Fig. 5a). As a consequence of the temperature variation, the relative humidity within the showcase follows the same dynamics as temperature (Fig. 5b). However, if the conditions of the case air-tightness worsened from $n = 0.008\ \text{h}^{-1}$ to $n = 0.017\ \text{h}^{-1}$, the rate of delaying and dampening effect of the showcase due to higher exfiltration/infiltration rates would decrease compared to the scenario with $n = 0.008\ \text{h}^{-1}$ as experienced in additional tests carried out (test E), while opposite effect occurred with increased air-tightness from $n = 0.008\ \text{h}^{-1}$ to $n \approx 0\ \text{h}^{-1}$ (test F). Based on the results obtained in test A, a second test (test B) has been carried out adding an extra thermal capacity in the technical compartment volume (5 gypsum plasterboards) to the standard showcase with

Table 2
External conditions in the climatic test chamber adopted for the experimental tests.

Test conditions	Description	HVAC system state
Heating	Steep increase of climatic chamber air temperature	On
Cooling	Steep decrease of climatic chamber air temperature	On
Thermal relaxation	Initial condition: showcase and climatic room air in non-thermal equilibrium with building air Final condition: thermal equilibrium Temperature not controlled	Off
Thermal drift	Initial condition: showcase air in non-equilibrium with preconditioned adsorbent substance. Final condition: hygrometric equilibrium Temperature not controlled	Off

Table 3
Relative errors in percentage (ave.; max) among measured and simulated conditions of showcase (T & RH) for different tests.

Test	T (ave.; max.)	RH (ave.; max.)
A	0.9; 1.7	2.8; 5.0
B	2; 7.6	11.2; 23.6
C	0.3; 0.8	2.0; 8.6
D	0.6; 1.4	1.3; 2.6
E	1.0; 1.8	9.9; 20.8
F	0.8; 2.7	2.3; 6.5

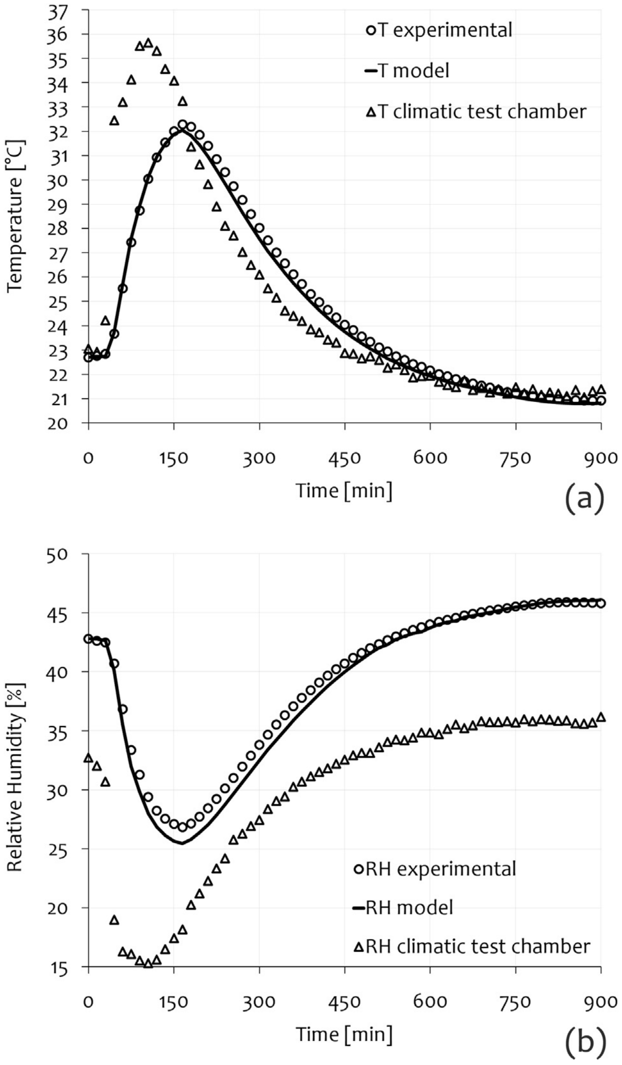

Fig. 5. Test A (heating and subsequent thermal relaxation). Display case in base configuration. Comparison of measured and simulated temperature trend (a), and measured and simulated relative humidity trend (b).

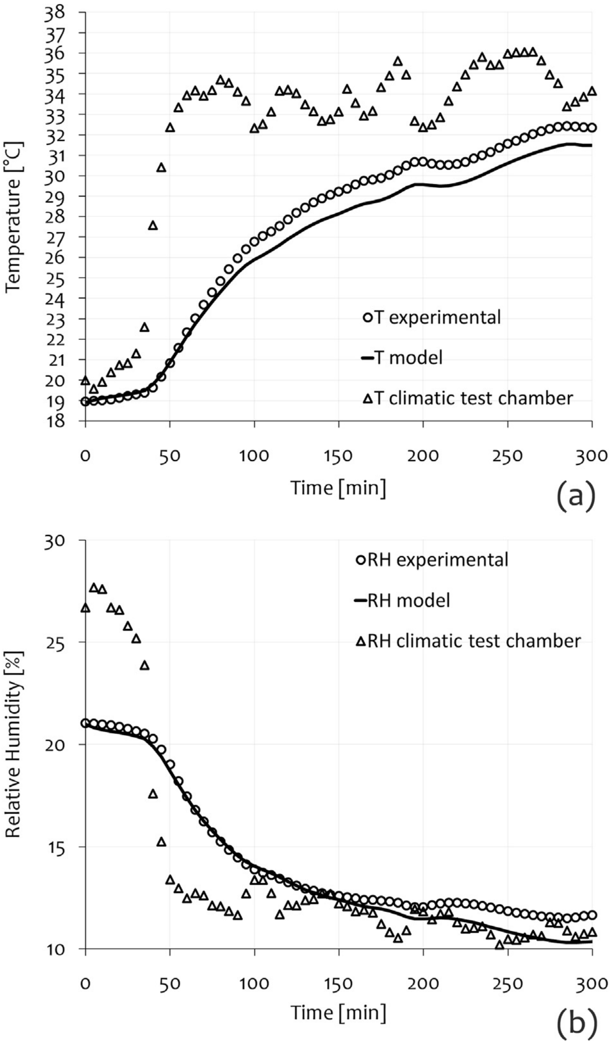

Fig. 6. Test B (heating). Display case in thermal capacity control configuration. Comparison of measured and simulated temperature trend (a), and measured and simulated relative humidity trend (b).

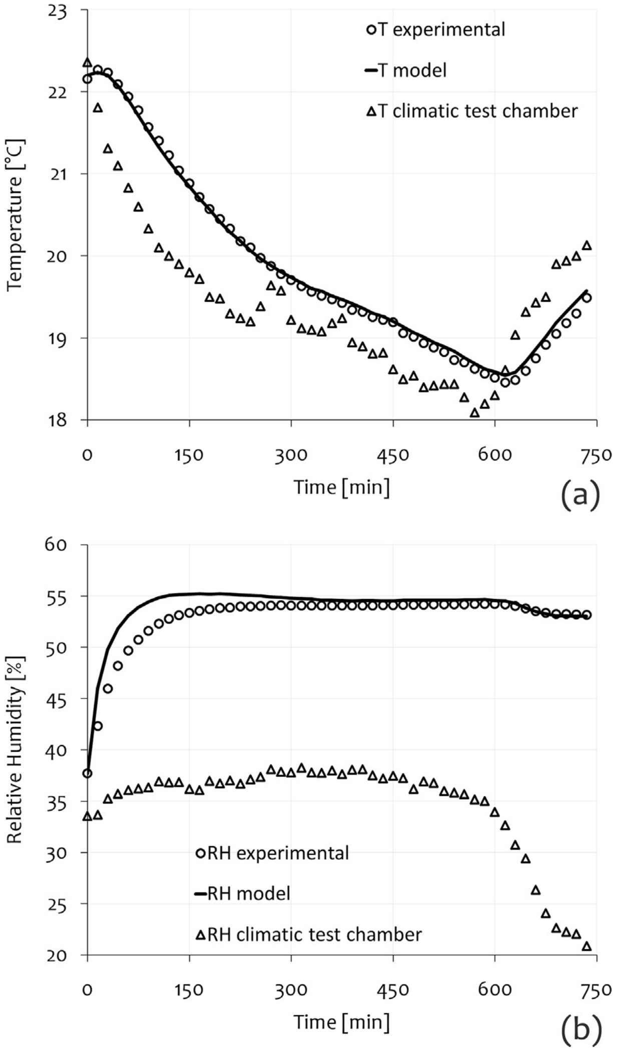

Fig. 7. Test C (thermal drift). Display case in adsorption capacity control configuration. Comparison of measured and simulated temperature trend (a), and measured and simulated relative humidity trend (b).

$n = 0.008\ h^{-1}$. In order to evaluate the performance of the extra ther-mal capacity added in the technical compartment, the showcase has been subjected to a steep temperature increase (heating con-figuration), followed by a thermal relaxation. Under this scenario, the showcase performance has shown good results in delaying and dampening the external temperature variations (see Fig. 6a). Exper-imental RH values agree with the modeled one except at low level of RH (see Fig. 6b) due to the uncertainty of the sensors used, while the predicted temperatures have always resulted few degrees under the measured ones (see Table 3).

A third test (test C) has been run inserting a known quantity of water adsorbent material (Artsorb®) within the exposition volume of the showcase. This test has been intended to assess the ability of the model in evaluating the condition of passive type show-cases, in terms of T and RH internal conditions, during a fault of the museum HVAC system. Thermal drift configuration of the test chamber has been used in this test, thus the external temperature slowly decreases (night-time) and then increases (day-time). The display case temperature follows the test chamber behavior. The modeled temperature of the showcase slightly disagrees from the measured one; moreover the temperature fluctuations of the test chamber are dampened by the thermal capacity of the adsorbent material (see Fig. 7a). Despite the small effect in controlling temperature, the adsorbent medium plays an important role in controlling internal humidity as shown in Fig. 7b. At the beginning of test C, the RH in the showcase was lower than the value set by the adsorbent preconditioning state (RH 55%). Thus, a quick increase of RH stabilizes the internal conditions to the substance preconditioning value. The rate of increase is strictly dependent on the adsorbent area and quantity. Later on, the stabilizing effect of the adsorbent material assures an almost constant internal humidity even in the presence of opposite temperature variations (initial external decrease followed by increase). The predictive ability of the model is in good agreement with the measured values for both the thermal drift scenario (test C) and the heating scenario (test D). The experimental setting of test D has been the same as test C except that the test chamber, and hence the showcase, faced a large increase in temperature over a period of five hours. Extra tests (test E and test F) have been carried out to evaluate the influence of the air-tightness on the showcase performance at its base configuration. Results have shown that higher values of n may worsen the internal condition of passive type showcase.

5. Conclusions

The simulation tool developed and experimentally validated in this study has proven to be a reliable tool to forecast the psychrometric conditions inside a showcase. Actually, the simulated conditions show a good agreement with experimental data: transient dynamics is well reproduced and the average deviation is always lower than about 2% for temperature, and about 11% for RH. These values are acceptable if compared with both the accuracy of the instrumentation and the uncertainty associated to the correlations used to compute heat transfer coefficients.

Thus, the proposed model can reasonably predict the behavior of the passive type showcase environment and could be used by display case designers and by conservation specialists as first tool in designing new passive type showcases or in case of existing ones to assess their performance (T, RH behaviors and air-tightness) under different external and internal scenarios. Future developments should include the influence of radiative and lighting sources even for active type showcases.

Acknowledgments

The authors wish to acknowledge Goppion S.p.A. for providing the showcase used in the experimental campaign and supporting this research.

References

[1] G. Pavlogeorgatos, Environmental parameters in museums, Build. Environ. 38 (2003) 1457–1462.

[2] D. Camuffo, G. Sturaro, A. Valentino, Showcases: a really effective mean for protecting artworks? Thermochim. Acta 365 (2000) 65–77.

[3] A. Schieweck, T. Salthammer, Indoor air quality in passive-type museum showcases, J. Cult. Herit. 12 (2011) 205–213.

[4] A.W.M. Van Schijndel, H.L. Schellen, J.L. Wijffelaars, K. van Zundert, Application of an integrated indoor climate. HVAC and showcase model for the indoor climate performance of a museum, Energ. Build. 40 (2008) 647–653.

[5] R.J.M. Lony, A.W.M. van Schijndel, H.L. Schellen, Evaluation of the climate control performance and reliability of active display cases, in: N.T. Bayazit, G. Manioğlu, G.K. Oral, Z. Yilmaz (Eds.), Proceedings of 4th International Building Physics Conference, Istanbul, May 15th–18th, 2009, pp. 679–686.

[6] L. Yu, H. Hou, X. Wan, H. Cheng, Study of the applications of a radiant cooling panel in museum showcases, in: Proceedings of 6th International Conference for Enhanced Building Operations, Shenzhen, November 6th–9th, 2006.

[7] H.J. Steeman, M. Van Belleghem, A. Janssens, M. De Paepe, Coupled simulation of heat and moisture transport in air and porous materials for the assessment of moisture related damage, Build. Environ. 44 (2009) 2176–2184.

[8] G. Thomson, Stabilization of RH in exhibition cases: hygrometric half-time, Stud. Conserv. 22 (1977) 85–102.

[9] G. Thomson, The museum environment, Butterworth-Heinemann, 1986.

[10] P. Brimblecombe, B. Ramer, Museum display cases and the exchange of water vapor, Stud. Conserv. 28 (1983) 179–188.

[11] D. Yu, S.A. Klein, D.T. Reindl, An evaluation of silica gel for humidity control in display cases, WAAC Newslett. 23 (2.) (2001).

[12] G.D. Raithby, G.T. Hollands, Natural convection, in: Heat Transfer Handbook, McGraw Hill, 1998.

[13] ESDU 77031, Heat transfer by free convection and radiation - simply shaped bodies in air and other fluids, IHS ESDU, 2008.

[14] A. Quarteroni, R. Sacco, F. Saleri, Numerical Mathematics, 2nd Edition, Springer, Berlin-Heidelberg, 2007.

[15] ISO 16000-8, Indoor air, determination of local mean age of air in buildings for characterizing ventilation conditions, International Organization for Standardization, Geneva, 2007.

List of symbols

C [J K^{-1}]: thermal capacity
H_{ads} [J kg^{-1}]: adsorbent heat of adsorption
M [kgs^{-1}]: mass flux
Q [W]: heat flux
R [K W^{-1}]: thermal resistance
R_m [kg s^{-1}]: mass advective resistance
RH [%]: relative humidity
T [$^\circ$C]: temperature
W [kg kg^{-1}]: adsorbent specific moisture content
m [kg]: mass
n [h^{-1}]: air change per hour
t [s]: time
x [kg kg^{-1}]: absolute humidity

Superscripts and subscripts

a: showcase air
a ads: air in contact with adsorbent substance surface
ads: adsorbent substance
adv: advective
cond: conductive
conv: convective
e: museum air
ext: external side
i: generic capacitive wall
inf: air infiltration
int: internal side
j: generic non-capacitive wall
th cap: passive temperature control system
vap: water vapor