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# THE APPLICATION OF VAPOUR-PERMEABLE SYNTHETIC MEMBRANES TO THE CLIMATIC STABILIZATION OF MUSEUM SHOWCASES

Carlo Isetti, Anna Magrini and Enrico Nannei

**Summary**—*This paper describes a novel technique to stabilize the relative humidity (RH) of the air inside museum showcases by using a synthetic hydrophobic membrane coupled with a hygroscopic solution in a membrane contactor. RH-monitoring data for two identical test cases, one of them controlled by a set-up with a plane-plate membrane contactor crossed by forced air and lithium chloride (LiCl) solution flows, show a significant stabilizing effect on RH fluctuations. A theoretical model permits forecasts in close agreement with the experimental RH data. Further calculations carried out over a one-year period show that notable damping of external RH variations can be obtained by using a low air circulation rate, small membrane surface area and low solution mass per unit case volume. A more general analytical solution in harmonic conditions is derived and discussed.*

## Introduction

Controlling the relative humidity (RH) of air inside museum showcases is very important to ensure the preservation of historic, artistic and cultural exhibits. In museum showcases, short-term fluctuations in RH are generally due to temperature changes, while long-term fluctuations are due to seasonal variations in the moisture content of the outside air.

The literature regarding these problems is copious. Two main aspects are considered in [1]: first, the environmental conditions to be controlled in museums and historic buildings, such as air-conditioning, lighting and air quality; and second, the environmental control of showcases.

The RH stabilization of showcases assumes a great importance when the climatic conditions of the museum are not controlled by any air-conditioning system. It is sometimes difficult to provide the whole museum environment with air-conditioning equipment, both for financial reasons and, in historic buildings, because of the many technical problems involved in installing such equipment. A simpler mechanical module system, requiring ductwork for the distribution of handled air and feeding directly controlled air into the case, has also been proposed [2].

Generally speaking, the hygric stabilization of a case may be achieved either by using active systems which can both humidify and dehumidify the air (by means of mechanical or thermoelectric devices), or by adopting passive control, that is, using hygroscopic materials. In general terms, it can be observed that an active system may bring about

sudden changes in the internal climatic conditions if the electronic control unit breaks down, while this would not happen with a passive system. When a passive system is used, RH fluctuations inside a case with limited air-exchange are reduced, due to the hygroscopic capacity of the interior materials.

Passive systems have been studied by many authors in order to ascertain the influence of different hygroscopic materials on the stabilization of the interior climate [3–8]. According to Thomson [4], a passive system needing no maintenance can control short-term fluctuations and maintain annual fluctuations around an average annual value corresponding to that of the surrounding air. When this value is not acceptable for conservation purposes, it becomes necessary to regenerate the hygroscopic materials periodically. A passive system can also take advantage of the high moisture capacity of non-saturated liquid solutions (saturated ones, obviously, have an infinitely great moisture capacity) which is considerably greater than that of the solid absorbing substances, such as silica gel, molecular sieves, Nikka pellets and so on, more usually employed.

At 50–60% RH, the vapour mass absorbed per unit mass of solution and per unit air RH% variation is about  $15\text{--}20\text{g.kg}^{-1}\text{RH}\%^{-1}$  for a non-saturated lithium chloride (LiCl) solution at 20°C [9]; by contrast, silica gel and Nikka pellets have lower values, ranging from 1 to  $4\text{g.kg}^{-1}\text{RH}\%^{-1}$  [4]. As a consequence, the protection against annual RH variations provided by 20kg of silica gel per cubic metre of case per year [4] can be accomplished with less than 5kg of a non-saturated LiCl solution.

The use of saturated solutions presents salt creeping problems [4] so that the adoption of vapour-

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permeable membrane mounted over the solution container has been suggested [8, 10]. Obviously, any air-gap between the liquid surface and the membrane, in order to avoid salt creeping in the case, will bring about a significant reduction in the efficiency of the mass transfer. For these set-ups the mass transfer is limited by the reduced contact surface area and by the low efficiency of natural convection mass transfer.

In this paper a new approach for the RH control of cases is proposed which overcomes the above-mentioned limitations.

The technique involves the use of a direct liquid-membrane contact, that is, the use of hydrophobic membranes which are permeable to vapour but impermeable to the solution in a membrane contactor with forced flow [11].

### RH stabilization of showcases using permeable membranes and hygroscopic solutions

The working principle of a hydrophobic membrane is based on the capillary phenomena due to the cohesive molecular bonds operating at the interface between each different phase in the membrane pores. The pressure necessary to force the liquid into the pores depends on the mean pore radius  $r$ , liquid surface tension and contact angle [12]. By controlling the pore radius of a hydrophobic membrane, it is possible to keep the liquid phase separate from the air, while maintaining a high water-vapour permeability by virtue of the open pores, which are unwetted by the liquid (Figure 1).

For instance, the pressure difference necessary to force pure water through a microfibre polyethylene (PE) membrane is about 10kPa. For a commercial microporous polytetrafluoroethene (PTFE) membrane, the entry pressure of the water into the pores is about 1300kPa for  $r = 0.45\mu\text{m}$  and increases to 2800kPa for  $r = 0.2\mu\text{m}$ . If the pore radius is

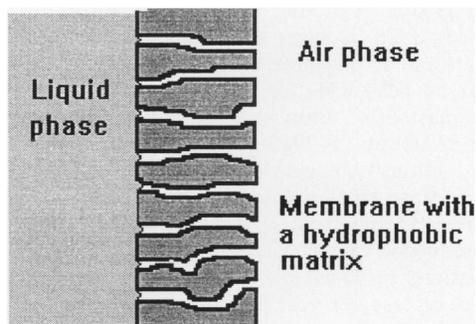


Figure 1 A hydrophobic membrane separating the air and the liquid phase.

reduced further, the entry pressure can reach 5000–6000kPa [13]. These membranes are manufactured up to 25–30 $\mu\text{m}$  thickness [14].

When aqueous salt solutions instead of pure water are considered, the membrane resistance to penetration by the liquid phase will be increased, since the liquid surface tension rises as the solute concentration increases, while it generally falls for aqueous solutions of organic compounds [15]. Membranes of this kind are already on sale, and are used in various fields.

In order to apply membrane technology to the RH stabilization of a showcase, a membrane contactor separating a suitable hygroscopic solution from a low-velocity air stream circulated from/to the case is considered. Plates and hollow fibre membrane contactors are employed in many fields of chemical engineering and can achieve high mass transfer surface per unit volume (typically 800m<sup>2</sup>m<sup>-3</sup> for plane plates, 2000m<sup>2</sup>m<sup>-3</sup> for hollow fibres [14]).

In conditions of thermodynamic equilibrium between the solution and the air, the RH of the air in contact with the solution is determined by the water activity in the liquid phase, which depends only on the solute concentration for a binary solution. The RH inside the case can therefore be controlled by means of the vapour transfer from/to the liquid phase to/from the recycled air taking place through the membrane. The RH of air inside a case can be chosen according to the composition of the hygroscopic solution and it will be as good as the temperature uniformity between the recycled air and the solution.

Such a system, for instance set in the bottom of the case, prevents salt pollution inside the case [4] since the membrane does not allow direct contact between the hygroscopic solution and the inside air. Moreover, the hygroscopic solution can also control the inside air quality by absorbing substances that are harmful to preservation, such as sulphur dioxide, nitrogen dioxide and ozone [4, 16–18]. For instance, quantities of Na<sub>2</sub>CO<sub>3</sub> or NaOH may be added to the solution to neutralize sulphur dioxide and nitrogen dioxide.

On the other hand, very thin membranes are delicate; they must therefore be free from imperfections to avoid any liquid leakage. The velocity of the recycled air in the membrane contactor should be limited in order to avoid a potential carry-over of solution droplets into the handled air in case of solution leakage from the membrane. Such precautions are essential when the exhibit is made of metal and the solution is corrosive.

In the absence of any regeneration, the solution concentration will cycle around an average annual value and the mass of the solution will contribute

to the whole moisture capacity of the case. On the other hand, by regenerating the solution, it is possible to keep the concentration RH constant and thus to maintain average annual RH values regardless of the external value.

When a regeneration process is used to keep the composition of the hygroscopic solution constant, provisions must be made for pure water to be added to or removed from the solution, for instance by adjusting the solution level in the container. If the level is low, it can simply be topped up by adding distilled water; if, on the other hand, excess water has to be removed, this operation can be performed by using a regeneration circuit equipped with a second membrane vapour contactor in contact with external heated air [14]. Optional plumbing for a centralized system might also be considered.

### Experimental set-up

In order to investigate RH stabilization inside cases by means of a membrane system and a hygroscopic LiCl solution, two tests were carried out over extended time-periods using two identical glass cases, one of which (CC) was controlled by the membrane system while the other (UC) had no passive control. The set-up sketched in Figure 2 was placed in a large basement storeroom without any climate control system.

The hygroscopic LiCl solutions were prepared with a 99% pure commercial-grade salt. The pH of

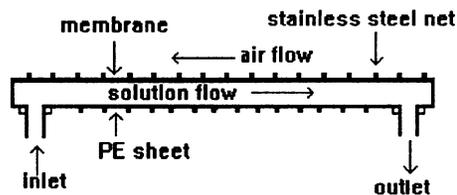


Figure 3 The vapour contactor.

the solution was checked and the observed residual acidity was neutralized with  $\text{NaHCO}_3$  additions up to pH 7.

A centrifugal pump with a 0.5m total head allowed a constant solution flow ( $\dot{m}_l = 3\text{g}\cdot\text{s}^{-1}$ , measured by direct weighing) to circulate from the solution container to the membrane contactor. The PTFE membrane had a  $0.04\text{m}^2$  exchanging surface facing a rectangular Plexiglas vane through which the air drawn from the case by a small fan flowed counter to the liquid flow.

The air crossed a vapour contactor 240mm long and 170mm wide (Figure 3) at a flow rate of  $\dot{m}_a = 0.15\text{g}\cdot\text{s}^{-1}$ . The mean air velocity in the section ( $170 \times 20\text{mm}$ ) was evaluated at  $2.7\text{cm}\cdot\text{s}^{-1}$ .

The average ventilation rate of the cases was evaluated by measuring the daily vapour mass adsorbed into a saturated LiCl solution (equilibrium air humidity 11% [19]) by means of a Sartorius BA 3100P analytical balance placed inside each case. The mean RH values of the air inside and outside the cases were also registered. The data obtained were used to compute the average ventilation rate

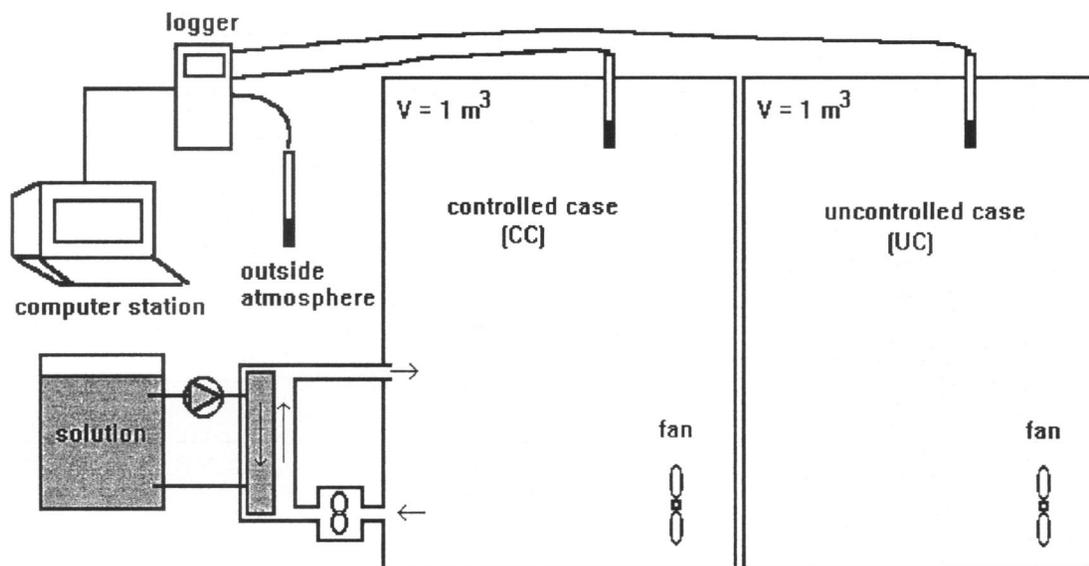


Figure 2 Experimental set-up.

of the cases by means of the vapour mass balance equations applied to the case volume in steady state conditions. A set of tests gave an average ventilation rate  $n = 0.98$  litre per day. The procedure outlined above is similar to the one used in [8].

The vapour contactor was made by thermally welding an impermeable polyethene sheet to a two-layer Gore-tex synthetic membrane. The Gore-tex membrane (PTFE on a supporting polypropene fibre layer) was set only on one side of the contactor, with the PTFE layer (about  $30\mu\text{m}$  thick,  $r = 0.45\mu\text{m}$  pore radius) facing the liquid and with the supporting layer (about  $670\mu\text{m}$  thick) facing the air.

The polypropene layer was welded to the impermeable polyethene sheet. The vapour contactor, shown in Figure 3, was contained in two rigid stainless-steel nets about 5mm apart, which created a rectangular flow section for the solution.

The air temperature and RH were monitored hourly by means of a four-channel Kane-May data-recording unit connected to probes reading both of these parameters, with a precision of  $\pm 2\%$  RH and  $\pm 1^\circ\text{C}$  temperature. Collected data were stored in files by means of a personal computer (PC).

## Results and discussion

The outside and inside RH values recorded over three months are depicted in Figure 4 for both UC and CC, and clearly show the stabilization due to the action of the membrane system. The air temper-

atures measured outside and inside the cases have the features outlined in Figure 4.

At the beginning of the first test, the LiCl solution ( $M = 4.1\text{kg}$ ) was in equilibrium at 58% RH, corresponding to a 20.4% mass composition of anhydrous LiCl [9].

Changes in the RH of the outside air had a negligible effect on the RH of the air inside CC, which was held close to the solution equilibrium value. In UC, however, only very short-term RH fluctuations appear to be smoothed. When the outside RH fell very sharply (from 88 to 30% in few hours) on day 47, the corresponding RH value inside CC was reduced from 62.5 to 59%; that is, the inside/outside RH variation ratio was 0.06.

A statistical analysis of the RH fluctuations was carried out to calculate the cumulative frequency distribution (F%) of the observed RH variations over two- and 24-hour intervals in sequence ( $\Delta\phi_2$ ,  $\Delta\phi_{24}$ ). Each F% distribution gives the percentage of the test time in which the RH variations (over two- and 24-hour intervals respectively) were less than the number given on the horizontal scale ( $\Delta\phi_2$  or  $\Delta\phi_{24}$ ). Obviously the difference ( $100 - F\%$ ) gives the time percentage in which the RH variations exceed  $\Delta\phi_2$  or  $\Delta\phi_{24}$ .

Figure 5 shows the F% distributions versus the  $\Delta\phi_2$  and  $\Delta\phi_{24}$  variations computed with the data collected outside and inside the cases. The cumulative frequency distribution F% versus  $\Delta\phi_2$  (Figure 5a) clearly shows the same stabilization effects, due to the limited air renewal and case volume, that UC

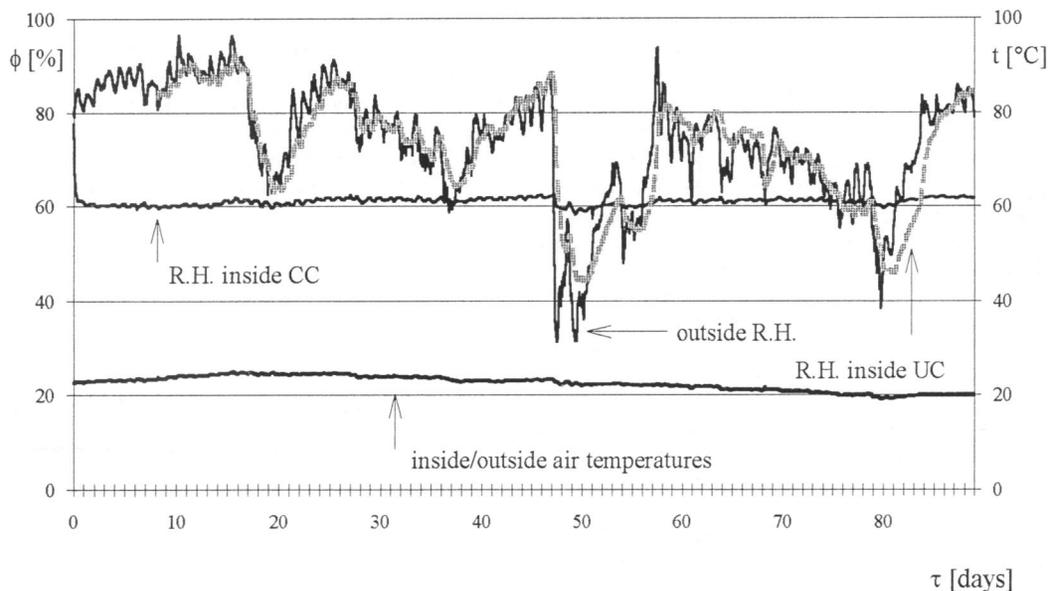


Figure 4 Outside/inside RH and air temperatures.

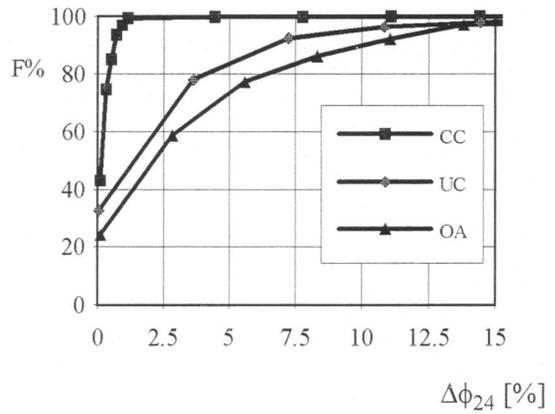
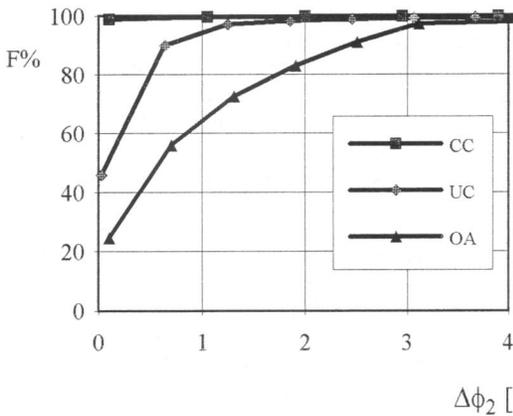


Figure 5 Cumulative frequency distribution  $F\%$  versus  $\Delta\phi_2$  (a) and versus  $\Delta\phi_{24}$  (b) in the outside air (OA), inside CC and UC.

manifests against RH fluctuations over two hours taking place in the outside air (OA). CC exhibits better control since it does not allow  $\Delta\phi_2$  fluctuations in RH greater than 0.5%, at least for 95% of the test time. The cumulative frequency distribution  $F\%$  versus  $\Delta\phi_{24}$  (Figure 5b) variations illustrate reduced stabilization efficiency in UC against RH fluctuations over 24 hours taking place in OA and, on the contrary, a remarkable stabilization effect in CC.

Finally, with reference to Figure 4, the RH increase inside CC, from 60 to 62%, can be ascribed to the dilution of the solution. The temperature profiles show an air-temperature uniformity inside the cases and in the surrounding environment during the tests.

In order to check the behaviour of the system at lower RH, another monitoring test with the same cases was carried out using a lower mass of LiCl solution ( $M = 1.25\text{kg}$ ) in equilibrium at a low relative air humidity of 33%, corresponding to a 30.9% mass composition of anhydrous LiCl [9, 11].

Figure 6 shows the RH values recorded outside and inside CC during a period of four weeks. The air temperature profiles measured inside the case and in the surrounding environment are also represented. Figure 6 again shows the stabilizing effect of the hygroscopic solution. The steeper gradient of the inside RH, from *c.* 38% up to *c.* 42% during the test time as compared with the three-month test, is due to the different solution masses used in the tests.

The cumulative frequency distributions  $\Delta\phi_2$  and  $\Delta\phi_{24}$  computed for the four-week test did not differ from those obtained in the three-month test, thus confirming that the influence of the solution mass on short-term fluctuations was negligible. The RH fluctuations appear to be controlled only by the solution mass and not by the surface area of the membrane and the air circulation rate. The air tem-

perature profiles reported in Figure 6 again show that negligible air-temperature differences occurred during the test.

In order to obtain an insight into the effect of an LiCl solution/hydrophobic membrane system on air quality, direct measurement of the overall corrosion potential of the air inside and outside CC was carried out, using metal samples.

The corrosion potential of airborne pollutants can be characterized by the build-up of various chemical-reaction products which form when the pollutants come into contact with specially-prepared copper coupons [20]. Two Purafil corrosion classification coupons were placed inside and outside CC during the three-month test [21]. At the end of the exposure time, electrolytic reduction analysis was performed on the coupons. This analysis revealed that, both inside and outside the controlled case, the concentration of contaminants was very low; both environments were therefore classifiable as ISA (Instrument Society of America) Class G1 severity (that is, corrosion is not expected to be

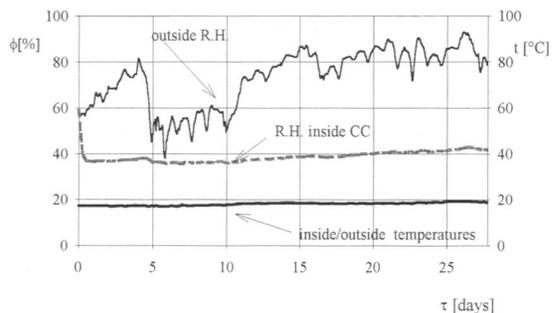


Figure 6 RH and air temperature outside/inside CC (four weeks monitoring).

a significant factor). These results show that the use of an LiCl solution/hydrophobic membrane system does not give rise to significant pollution of the indoor air by airborne contaminants such as solution droplets. Further tests are planned in order to study in more detail the possibility of controlling the air quality inside the case when polluting substances are present in the outside air.

In order to study the behaviour of the system as a function of the main parameters (solution mass, membrane exchanging surface, case volume, average ventilation rate, air and solution flow rate, solution characteristics), a theoretical model was developed. Details are given in Appendix 1.

The system of the governing equations (eq. (6'), (7'), (8') in Appendix 1) is not linear since  $M = f(\tau)$ ,  $c^*_1 = f(a_w) = f'(M)$  and a logarithmic function of  $p_{v1}$ ,  $p_{v2}$  is present, so that for its numerical solution an explicit method marching in time was used. The time-step considered (one hour) allowed a stability of the numerical solution. An analytical solution in harmonic conditions is derived in Appendix 2 and briefly discussed with its simplifying assumption.

The measured air RH values inside CC are compared with the theoretical forecast computed using the hourly RH data of the outside air recorded from day 47 to day 53 as input conditions. In Figure 7 a very close agreement between the measured and the computed values can be observed.

For the two-layered membrane, calculations were performed considering a diffusion resistance factor  $\mu = 6$  for the 30 $\mu$ m-thick PTFE layer and a resistance factor  $\mu = 1$  for the supporting layer. The Chilton-Coburn relation between heat and mass transfer coefficients in the air phase [22] was used to evaluate the mass transfer coefficient that resulted  $\beta = 6.16 \times 10^{-8} \text{kg.m}^{-2}\text{s}^{-1}\text{Pa}^{-1}$ . The calculated heat transfer coefficient at the air side of the membrane was  $h_{ca} = 9 \text{W.m}^{-2}\text{K}^{-1}$ , as a result of the low air velocity through the rectangular vane of the membrane contactor [23].

Adopting an air vapour permeability  $\delta_{va} = 193 \times 10^{-12} \text{kg.m}^{-1}\text{s}^{-1}\text{Pa}^{-1}$  [24] the overall mass transfer coefficient becomes  $K_v = 4.85 \times 10^{-8} \text{kg.m}^{-2}\text{s}^{-1}\text{Pa}^{-1}$ . The specific moisture capacity of the air was  $c_a = 0.622/p_a$  while properties of the LiCl solution [9] allow  $c^*_1$  to be computed easily as a function of solution mass composition.

### Numerical investigation in annual-cycle conditions

The theoretical model has been used to investigate the behaviour of RH in annual cycles. As shown in [25] the partial vapour pressure  $p_v(\tau)$  in outdoor air for Genoa can be represented by a deterministic component and a stochastic component  $\epsilon(\tau)$  by means of the following relations:

$$p_v(\tau) = a^0 + \sum_{j=1}^{j=2} \left[ a^j \cos\left(j \frac{2\pi}{\tau_0} \tau\right) + \psi^j \right] + \epsilon(\tau)$$

The stochastic component  $\epsilon(\tau)$  (nearly Gaussian) is typical of the short term, while in the annual period the deterministic component is more important and is determined mainly by the amplitude of the fundamental harmonic  $a^1$  (one-year period).

For the sake of simplicity and in order to indicate the influence of the principal parameters of a passive membrane working in annual cycles, a simple cosine variation of the vapour pressure as:

$$p_v(\tau) = a^0 + \Delta p_{eo} \cos \frac{2\pi\tau}{\tau_0}$$

was considered, in the present numerical investigation, with a reference amplitude  $\Delta p_{eo} = 500 \text{Pa}$  as compared with an average value  $a^0 = 1235 \text{Pa}$ .

Calculations refer to a passive system using a LiCl solution and a contactor with a vapour-exchanging surface per unit case volume  $S/V = 0.040 \text{m}^2\text{m}^{-3}$ , an air circulation rate per unit volume  $\dot{m}_a/V = 0.15 \text{g.m}^{-3}\text{s}^{-1}$  and a case ventilation rate  $n = 1$  litre per day. The membrane has the same characteristics as that adopted for the preced-

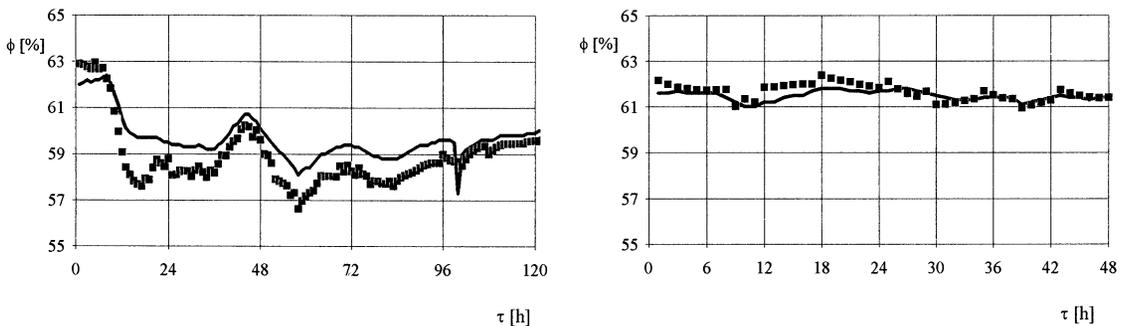


Figure 7 Theoretical (dotted line) and experimental (solid line) results inside CC.

ing calculations. The absorption system and the inside and outside air were assumed to be at a constant temperature of 20°C.

The average solution composition is in equilibrium with the average annual RH of the outside air (55%); the same RH inside the case can therefore be maintained by means of passive buffering without controlling the solution concentration at all.

In Figure 8 the numerically computed RH variation in OA (solid line) and that inside CC (broken line) are shown for  $M/V = 5\text{kg}\cdot\text{m}^{-3}$ . The outside RH variation appears significantly damped by the buffering effect of the solution mass. Inside CC, the RH variation presents a phase shift of about 50 days compared with the OA RH, which cycles around the average annual RH of 55%.

Further calculations were carried out in order to determine the influence on the stabilization efficiency (damping effect) of the most important parameters with regard to the unit case volume: the solution mass  $M/V$ , the product of the mass transfer coefficient and the membrane surface  $K_v S/V$  and the air circulation rate  $\dot{m}_a/V$ .

Figure 9 shows the relationship between the computed damping ratio  $A^* = \Delta p_{vi}/\Delta p_{eo} = \Delta \phi_i/\Delta \phi_{eo}$  around the average RH level of 55% and the parameter  $K_v S/V$  ( $S/V = 0.04\text{m}^2\cdot\text{m}^{-3}$ ) for ventilation rate  $n$  ranging from 0.5 to 1.5 litre per day. A mass of LiCl solution per unit volume  $M/V = 5\text{kg}\cdot\text{m}^{-3}$  and an air circulation rate of  $\dot{m}_a/V = 0.15\text{g}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$  were assumed.

These results show that an increase in  $K_v S/V$  to above  $0.20 \times 10^{-8}\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$  has a very slight effect on the damping ratio  $A^*$ ; thus, to get a damping ratio  $A^* < 0.1$ , at least for  $n = 1$  litre per day and  $K_v = 4.85 \times 10^{-8}\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$ , a membrane surface per unit volume of  $S/V 0.04\text{m}^2\cdot\text{m}^{-3}$  will suffice.

Figure 10 reports the computed damping ratio  $A^* = \Delta p_{vi}/\Delta p_{eo}$  as a function of  $M/V$  for a case ventilation rate  $n$  ranging from 0.5 to 1.5 litre per day. A product  $K_v S/V = 0.20 \times 10^{-8}\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$

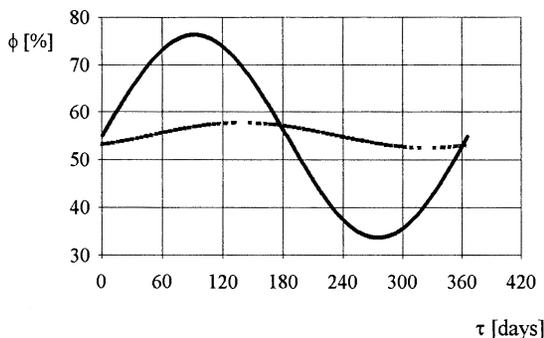


Figure 8 Annual hygrometric harmonic conditions for CC (broken line) and OA (solid line) at constant temperature.

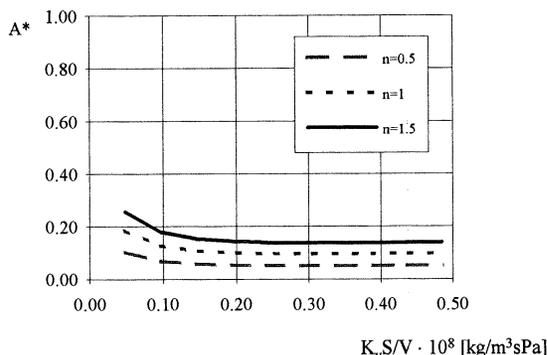


Figure 9 Damping effect as a function of  $K_v S/V$  for various ventilation rates  $n$  [litres per day].

( $S/V = 0.04\text{m}^2\cdot\text{m}^{-3}$ ) is assumed. These results show that a LiCl solution mass per unit volume of about  $M/V = 3\text{kg}\cdot\text{m}^{-3}$  will be enough to achieve a damping ratio  $A^* < 0.1$  of the outside RH amplitude, at least for a case ventilation rate  $n = 1$  litre per day,  $\dot{m}_a/V = 0.15\text{g}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$  and  $K_v = 4.85 \times 10^{-8}\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$ . Other solutions with a lower specific moisture capacity, for instance solutions of organic substances such as glycerol (propane-1,2,3-triol), will require larger masses to achieve the same results, on account of their lower specific moisture capacity  $c^*$ .

Figure 11 reports the computed damping ratio  $A^* = \Delta p_{vi}/\Delta p_{eo}$  as a function of  $\dot{m}_a/V$  for a case ventilation rate  $n$  ranging from 0.5 to 1.5 litre per day. A product  $K_v S/V = 0.20 \times 10^{-8}\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$  ( $S/V = 0.04\text{m}^2\cdot\text{m}^{-3}$ ) and  $M/V = 5\text{kg}\cdot\text{m}^{-3}$  are assumed. These results show that an air circulation rate of about  $\dot{m}_a/V = 0.2\text{g}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$  will be enough to achieve a damping ratio  $A^* < 0.1$  of the outside RH amplitude, at least for a case ventilation rate  $n = 1$  litre per day,  $M/V = 5\text{kg}\cdot\text{m}^{-3}$  and  $K_v = 4.85 \times 10^{-8}\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}\cdot\text{Pa}^{-1}$ .

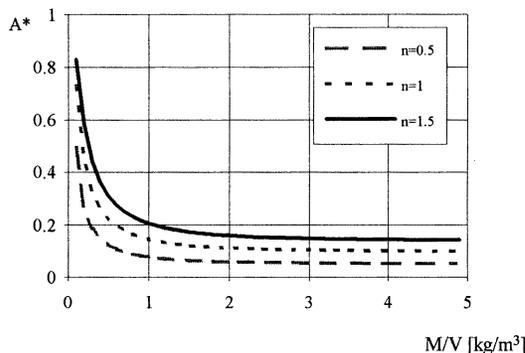


Figure 10 Damping effect as a function of  $M/V$  for various ventilation rates  $n$  [litres per day].

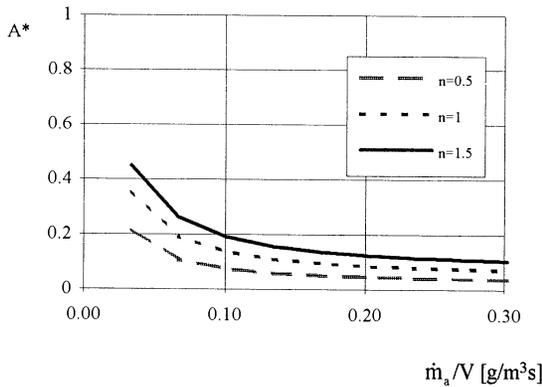


Figure 11 Damping effect as a function of  $\dot{m}_a/V$  for various ventilation rates  $n$  [litres per day].

**Conclusions**

The passive control method described in this paper offers a viable means of controlling the RH of air inside limited air-exchanging enclosures, as shown by the experimental investigation.

The experiments carried out with different masses of a LiCl solution were compared with the theoretical predictions by means of a numerical model. A close agreement between the recorded and the computed results was obtained.

Analysis performed on Purafil corrosion classification coupons after three months of test exposure showed that metal corrosion inside the controlled case is not expected to be a significant factor.

Long-term simulation showed that reduced membrane surfaces, air circulation rates and solution masses per unit case volume are sufficient to obtain sensible damping of the outside RH oscillations and to maintain the average RH of the surrounding air.

This passive system seems well-suited to controlling RH inside museum cases or similar applications.

Further research is planned to investigate the possibility of using a membrane system to safeguard the quality of indoor air against pollutants which can jeopardize conservation.

**Appendix 1: The theoretical model**

*Water transfer through a hydrophobic membrane contactor in isothermal conditions: case and solution mass balances*

The vapour flux through the pore-space of a non-wetted porous membrane is determined by various mechanisms, such as the water mass transfer in the liquid phase, evaporation/condensation at the liquid interface, the non-equimolar vapour flux across the

stagnant air film in the pores and the convective vapour transfer on the air side.

In isothermal conditions, the vapour mass flux  $dG_p$  exchanged with the solution surface  $dS$  can be expressed by [14, 26]:

$$dG_p = K_v(p_v - p_v^*)dS \tag{1}$$

The equilibrium vapour pressure  $p_v^*$  is related to the thermodynamic activity of water  $a_w = y_w \gamma_w$  in the solution as follows:

$$p_v^* = a_w p_s = y_w \gamma_w p_s \tag{2}$$

The equilibrium vapour pressure  $p_v^*$  can also be related to the molar water concentration  $d_w$ , according to Henry's law ( $p_v^* = m d_w$ ); thus the  $m$  coefficient may be written as:

$$m = \gamma_w p_s / d_w = y_w \gamma_w p_s / d_w \tag{3}$$

The mass transfer coefficient  $K_v$  depends on the membrane resistance to the vapour transfer  $\ell \mu / \delta_{va}$  and on both liquid and air side convective resistances  $m / M_w k_l$  and  $1/\beta$ :

$$K_v = (m / M_w k_l + 1/\beta + \ell \mu / \delta_{va})^{-1} \tag{4}$$

For low mass fluxes,  $K_v$  reduces to  $(1/\beta + \ell \mu / \delta_{va})^{-1}$  as the resistance to water transport in the liquid phase is negligible [26].

The variation of the water molar fraction in the solution due to the exchange of a vapour mass  $dM_v$  is  $dy_w = dM_v / (N_l M_w)$ . As a consequence, according to Raoult's law in isothermal conditions, the resulting equilibrium pressure variation is  $dp_v^* = \gamma_w p_s dy_w$ .

Defining the specific moisture capacity of the solution as  $c_l^* = dM_v / (M_l dp_v^*)$  and the specific moisture capacity of the air as  $c_a = dM_v / (M_a dp_v)$ , the mass flow rate  $dm_{2v}$  through an incremental membrane surface  $dS$  of a counter-current flow contactor may be related to both  $dp_v$  and  $dp_v^*$  in the air stream and solution flow as:

$$dG_p = -\dot{m}_a c_a dp_v \tag{5}$$

$$dG_p = -\dot{m}_l c_l^* dp_v^* \tag{5'}$$

If the mass flow rates and the specific capacities  $c_a$  and  $c_l^*$  are constant in the contactor, by combining equations (1), (5) and (5') the vapour flow rate exchanged across the contactor can be evaluated in relation to the exchanging surface  $S$  and to a logarithmic mean vapour pressure difference between the air and the solution:

$$G_p = K_v S \Delta p_{ln} \tag{6}$$

where  $\Delta p_{ln} = (\Delta_1 - \Delta_2) / \ln \Delta_1 / \Delta_2$  with  $\Delta_1 = (p_{v1} - p_{v1}^*)$  and  $\Delta_2 = (p_{v2} - p_{v2}^*)$  [inlet (section 1) and outlet (section 2)];  $p_{v1} = p_{v1}$ . Its meaning is the

same as the logarithmic mean temperature difference in heat exchanger practice [27].

The solution activity along the contactor is assumed constant (i.e.,  $p_{v2}^* = p_{v1}^* = p_v^*$ ) because the  $c_1^*/c_a$  ratio is greater than 100 for a LiCl solution and  $\dot{m}_1/\dot{m}_a$  is greater than 1.

A water mass balance of the solution control volume gives:

$$M c_1^* \frac{dp_v^*}{dt} = S K_v \Delta p_{in} + \dot{m}_v \quad (7)$$

where  $\dot{m}_v = f(\tau)$  is the water flow rate added to or removed from the solution; for a system without a regeneration mechanism it is  $\dot{m}_v = 0$ .

### Vapour balance of the case

By assuming single-zone approximation, i.e., inside air characterized only by the vapour pressure  $p_{vi}$ , outside air entering through leaks is characterized by the vapour pressure  $p_{ve}$  and perfect mixing, the vapour balance equation is:

$$\frac{V}{R_v T_i} \frac{dp_{vi}}{dt} = G_v + n \frac{V}{R_v T_i} (p_{ve} - p_{vi}) \quad (8)$$

where  $G_v = -G_p$ .

With reference to a system without solution regeneration, the system of differential equations per unit case volume can be written as:

$$-\frac{\dot{m}_a}{V} c_a (p_{v2} - p_{vi}) = K_v \frac{S}{V} \Delta p_{in} \quad (6')$$

$$\frac{M}{V} c_1^* \frac{dp_v^*}{dt} = \frac{S}{V} K_v \Delta p_{in} \quad (7')$$

$$\frac{dp_{vi}}{dt} + n(p_{vi} - p_{ve}) = -R_v T_i \frac{S}{V} K_v \Delta p_{in} \quad (8')$$

## Appendix 2: Analytical solution in harmonic conditions

By taking the simplification:

$$G_p = K_v S \Delta p_{in} \cong K_v S \Delta p_{av}$$

where  $\Delta p_{av} = [(p_{v1}^* - p_{v1}^*) + (p_{v2} - p_{v2}^*)]/2$ , ( $p_{v1} = p_{vi}$  and  $p_{v1}^* = p_{v2}^* = p_v^*$ ), the system of differential equations to be solved reduces to:

$$-\frac{\dot{m}_a}{V} c_a (p_{v2} - p_{vi}) = K_v \frac{S}{V} \Delta p_{av} \quad (6')$$

$$\frac{M}{V} c_1^* \frac{dp_v^*}{dt} = \frac{S}{V} K_v \Delta p_{av} + \dot{m}_v \quad (7')$$

$$\frac{dp_{vi}}{dt} + n(p_{vi} - p_{ve}) = -R_v T_i \frac{S}{V} K_v \Delta p_{av} \quad (8')$$

In the absence of any solution regeneration ( $\dot{m}_v = 0$ ), assuming the product  $c_1^* M/V$ ,  $K_v$  and temperature  $T_i$  to be constant, the system becomes linear; therefore, an exact analytical solution is possible in steady-state periodic variation of the outside vapour pressure  $p_{ve}$ . Obviously, neither the solution mass  $M$  nor  $c_1^*$  are constant, as a consequence of the vapour exchanges occurring with the solution. The approximation becomes appropriate when the solution mass  $M$  is great compared with the water mass adsorbed/desorbed in the harmonic cycle, and consequent variations in water activity are slight. By adopting these simplifications, it is possible to write:

$$p_{ve} = \Delta p_{ve} + \bar{p}_{ve} \quad \Delta p_{ve} = \Delta p_{eo} e^{i\omega\tau} \quad p_{ve} - \bar{p}_{ve} = \Delta p_{eo} e^{i\omega\tau}$$

thus:

$$\begin{aligned} p_{vi} &= \Delta p_{vi} + \bar{p}_{vi} & \Delta p_{vi} &= A e^{i\omega\tau} & p_{vi} - \bar{p}_{vi} &= A e^{i\omega\tau} \\ p_v^* &= \Delta p_v^* + \bar{p}_v^* & \Delta p_v^* &= B e^{i\omega\tau} & p_v^* - \bar{p}_v^* &= B e^{i\omega\tau} \\ p_{v2} &= \Delta p_{v2} + \bar{p}_{v2} & \Delta p_{v2} &= C e^{i\omega\tau} & p_{v2} - \bar{p}_{v2} &= C e^{i\omega\tau} \end{aligned}$$

By using complex numbers, the differential system reduces to an algebraic system which allows the constants  $A$ ,  $B$  and  $C$  to be determined.

The solution in harmonic conditions gives:

$$\begin{aligned} p_{vi} &= \bar{p}_{vi} + A e^{i\omega\tau} = \bar{p}_{vi} + A^* \Delta p_{eo} e^{i(\omega\tau - \psi_{11})} \\ p_v^* &= \bar{p}_v^* + B e^{i\omega\tau} = \bar{p}_v^* + B^* \Delta p_{eo} e^{i(\omega\tau - \psi_{11} - \psi_{22})} \\ p_{v2} &= \bar{p}_{v2} + C e^{i\omega\tau} = \bar{p}_{v2} + C^* \Delta p_{eo} e^{i(\omega\tau - \psi_{11} - \psi_{33})} \end{aligned}$$

and for the mean values:

$$p_{vi} = p_{v2} = p_{ve} = p_v^*$$

Finally, by taking only the real part of the complex oscillations, the result is:

$$\begin{aligned} p_{vi} &= \bar{p}_{vi} + A^* \Delta p_{eo} \cos(\omega\tau - \psi_{11}) \\ p_v^* &= \bar{p}_v^* + B^* \Delta p_{eo} \cos(\omega\tau - \psi_{11} - \psi_{22}) \\ p_{v2} &= \bar{p}_{v2} + C^* \Delta p_{eo} \cos(\omega\tau - \psi_{11} - \psi_{33}) \end{aligned}$$

where

$$A^* = \frac{n}{\sqrt{x^2 + z^2}} \quad B^* = \frac{A^*}{(c_1^* M/V) \omega \sqrt{x^2 + y^2}}$$

$$C^* = A^* \sqrt{1 - \frac{2x(c_a \dot{m}_a/V) - 1}{(c_a \dot{m}_a/V)^2 (x^2 + y^2)}}$$

$$x = \frac{V}{K_v S} + \frac{V}{c_a \dot{m}_a}; \quad z = \frac{V}{c_1^* M} \frac{1}{\omega}; \quad x^* = n + \frac{R_v T_i}{x^2 + z^2} x$$

$$z^* = \omega + \frac{R_v T_i}{x^2 + z^2} z$$

$$A = \frac{n \Delta p_{eo}}{\sqrt{x^2 + z^2}} e^{-i\psi_{11}};$$

$$B = \frac{V}{c_1^* M} \frac{A}{\omega \sqrt{x^2 + z^2}} e^{-i\psi_{11}}$$

$$C = A \sqrt{1 - \frac{2(c_a \dot{m}_a/V)x - 1}{(c_a \dot{m}_a/V)^2(x^2 + z^2)}} e^{-i\psi_{11}}$$

$$\psi_{11} = \arctg \frac{z^*}{x^*} \quad \psi_{22} = \arctg \frac{x}{z}$$

$$\psi_{33} = \arctg \frac{z}{(c_a \dot{m}_a/V)(x^2 + z^2) - x}$$

A comparison between analytical results obtained with a LiCl solution having an average  $c_1^* = 0.65 \text{ g.kg}^{-1} \text{ Pa}^{-1}$  at 55% RH and the corresponding numerical results of Figures 9, 10 and 11 shows that, for  $n = 1$  litre per day,  $\dot{m}_a/V = 0.15 \text{ gm}^{-3} \text{ s}^{-1}$ ,  $S/V = 0.04 \text{ m}^2 \text{ m}^{-3}$ , the differences between the corresponding damping ratios are less than 15%, at least for  $M/V > 5 \text{ kgm}^{-3}$ .

It is worth noting that this analytical solution in harmonic conditions can also hold for a system working with a constant solution concentration (i.e., perfect regeneration) if one takes a high  $M/V$  ratio so that  $p_v^* = \text{constant}$  and  $B^* = 0$ .

### Appendix 3: Symbols

- $a^j$  = amplitude of the  $j^{\text{th}}$  harmonic [Pa]
- $a$  = thermodynamic activity [–]
- $A^*$  = damping ratio in harmonic conditions =  $\Delta p_{vi}/\Delta p_{eo}$  [–]
- $c$  = specific moisture capacity [ $\text{kg.kg}^{-1} \text{ Pa}^{-1}$ ]
- $c_1^*$  = hygroscopic specific capacity of the solution [ $\text{kg.kg}^{-1} \text{ Pa}^{-1}$ ]
- $d$  = concentration [ $\text{kmole.m}^{-3}$ ]
- $d_t$  = water + solute concentration [ $\text{kmole.m}^{-3}$ ]
- $F_0^{\%}$  = cumulative frequency distribution [–]
- $G_v$  = vapour mass flow referred to the case [ $\text{kg.s}^{-1}$ ]
- $G_p$  = vapour mass flow referred to the solution mass [ $\text{kg.s}^{-1}$ ]
- $k$  = mass transfer coefficient [ $\text{m.s}^{-1}$ ]
- $K_v$  = isothermal overall mass transfer coefficient [ $\text{kg.m}^{-2} \text{ s}^{-1} \text{ Pa}^{-1}$ ]
- $h_{ca}$  = heat transfer coefficient at air side of the membrane [ $\text{W.m}^{-2} \text{ K}^{-1}$ ]
- $\ell$  = membrane thickness [m]
- $m$  = proportionality coefficient (Henry's law) [ $\text{Pa.m}^{-3} \text{ kmole}^{-1}$ ]
- $M$  = molecular mass [ $\text{kg.kmole}^{-1}$ ]
- $M$  = mass [kg]
- $\dot{m}$  = mass flow [ $\text{kg.s}^{-1}$ ]
- $N$  = number of moles [–]
- $n$  = ventilation rate [ $\text{l.s}^{-1}$ ] or [ $\text{l.day}^{-1}$ ]
- $p$  = pressure [Pa]

- $\bar{p}$  = mean pressure value [Pa]
- $p_v$  = partial vapour pressure [Pa]
- $p_v^*$  = partial vapour pressure in equilibrium with the solution [Pa]
- $\Delta p_{eo}$  = amplitude of the harmonic variation in outside vapour pressure [Pa]
- $\Delta p_{in}$  = logarithmic mean vapour pressure difference [Pa]
- $\Delta p_{av}$  = average vapour pressure value =  $[(p_{vi} - p_v^*) + (p_{v2} - p_v^*)]/2$  [Pa]
- $r$  = pore radius [m]
- $R_v$  = gas constant for the vapour [ $\text{J.kg}^{-1} \text{ K}^{-1}$ ]
- $S$  = membrane surface of the vapour contactor [ $\text{m}^2$ ]
- $t$  = temperature [ $^{\circ}\text{C}$ ]
- $T$  = absolute temperature [K]
- $V$  = case volume [ $\text{m}^3$ ]
- $y$  = molar fraction [–]
- $\beta$  = coefficient of mass transfer moist air/membrane surface [ $\text{kg.m}^{-2} \text{ s}^{-1} \text{ Pa}^{-1}$ ]
- $\gamma$  = activity factor [–]
- $\delta_{va}$  = vapour permeability in still air [ $\text{kg.m}^{-1} \text{ s}^{-1} \text{ Pa}^{-1}$ ]
- $\varepsilon$  = stochastic component of pressure [Pa]
- $\mu$  = membrane resistance factor to the vapour transmission [–]
- $\psi^j$  = phase shift of the  $j^{\text{th}}$  harmonic [rad]
- $\psi_{11}$  = phase shift between  $p_{vi}$  and  $p_{ve}$  [rad]
- $\psi_{22}$  = phase shift between  $p_v^*$  and  $p_{vi}$  [rad]
- $\psi_{33}$  = phase shift between  $p_{v2}$  and  $p_{vi}$  [rad]
- $\phi$  = relative air humidity [–]
- $\Delta \phi_{eo}$  = reference amplitude of the harmonic variation in outside RH [–]
- $\Delta \phi_2$  = RH variation over two-hour intervals [–]
- $\Delta \phi_{24}$  = RH variation over 24-hour intervals [–]
- $\tau$  = time [s]
- $\tau_o$  = one-year period [s]
- $\omega$  = angular frequency [ $\text{rad.s}^{-1}$ ]

### Subscripts

- $a$  = related to the air phase
- $e$  = related to the outside environment
- $i$  = related to the inside case environment
- $l$  = related to the liquid phase
- $s$  = related to saturation conditions
- $t$  = related to total
- $v$  = related to the vapour phase
- $w$  = related to water
- $1, 2$  = related to the inlet and outlet sections of the contactor

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## References

- 1 HAIAD, J.C., DRUZIK J., AYRES, J.M., and LAU H., 'Museum environmental requirements: a literature survey', *ASHRAE Transactions* **96**(2) (1990) 112.
- 2 MICHALSKI, S., 'A control module for RH in display cases' in *Science and Technology in the Service of Conservation*, IIC, London (1982) 28–31.
- 3 BIAVA, S., CAON, S., FILIPPI, M., and LOMBARDI, C., 'Sperimentazioni su un prototipo di vetrina museale corredato di un sistema passivo per il controllo igrometrico' in *Proceedings 47th National Congress ATI (Associazione Termotecnica Italiana)*, Parma (1992) 421–433.
- 4 THOMSON, G., *The Museum Environment*, 2nd edn, Butterworth–Heinemann, London (1986).
- 5 WEINTRAUB, S., 'A new design for a low maintenance silica-gel system for the control of relative humidity in a sealed case' in *Conservation Within Historic Buildings*, IIC, London (1980) 55–56.
- 6 GUICHEN, G., and GAI, V., 'Contrôle du climat autour de 197 instruments de musique' in *ICOM Committee for Conservation 7th Triennial Meeting*, Copenhagen (1984).
- 7 RAMER, B., 'The development of a local humidity control system', *International Journal of Museum Management and Curatorship* **3**(2) (1984) 183–191.
- 8 PADFIELD, T., 'The control of relative humidity and air pollution in show-cases and picture frames', *Studies in Conservation* **11** (1966) 8–30.
- 9 GAZINSKI, E., and SZCZECOWIAK, E., 'Die thermodynamischen Grundlagen der Luftfeuchtigkeit mit Hilfe der wässrigen Lithiumbromid- und Lithiumchlorid-Lösungen', *Ki Klima-Kälte 1* (1984) 509–514.
- 10 CREAHAN, J., 'Controlling relative humidity with saturated calcium nitrate solutions', *WAAC Newsletter* **13**(1) (1991) 17–18.
- 11 ISETTI, C., and MAGRINI, A., 'Controllo passivo dell'igrometria ambientale di vetrine museali: applicazione di una nuova metodologia' in *Proceedings 50th National Congress ATI (Associazione Termotecnica Italiana)*, Saint Vincent (1995) 933–944.
- 12 ADAMSON, A.W., *Physical Chemistry of Surfaces*, Interscience Publishers Inc., New York (1960).
- 13 ORTIZ DE ZARATE, J.M., VELAZQUEZ, A., *et al.*, 'Non-isothermal solute transport through PTFE membranes', *Journal of Membrane Science* **69** (1992) 169–178.
- 14 ISETTI, C., MAGRINI, A., and NANNEI, E., 'Feasibility of a membrane air-liquid contactor for air dehumidification and conditioning' in *Proceedings Healthy Buildings International Conference*, Milan (1995) 1531–1536.
- 15 PERRY, R.H., *et al.*, *Chemical Engineers' Handbook*, McGraw-Hill Book Company, New York (1984).
- 16 WHITMORE, P.M., and CASS, G.R., 'The fading of artists' colorants by exposure to atmospheric nitrogen dioxide', *Studies in Conservation* **34** (1989) 85–97.
- 17 SHAVER, C.L., CASS, G.R., and DRUZIK, J.R., 'Ozone and the deterioration of works of art', *Environmental Science and Technology* **17** (1983) 748–752.
- 18 GIBBENS, H.R., POPE, D., and MOSS, R.L., 'Removal of sulfur dioxide from a simulated museum atmosphere using carbon filters', US Department of Commerce, National Technical Information Service, Springfield VA (1985).
- 19 GREENSPAN, L., 'Humidity fixed points of binary saturated aqueous solutions', *Journal of Research of National Bureau of Standards—A. Physics and Chemistry* **81A**(1) (1977).
- 20 ISA Committee SP71, Standard ISA-S71.04, *Environmental Conditions for Process Measurement and Control Systems: Airborne Contaminants*, Instrument Society of America, Research Triangle Park, NC (1985).
- 21 Purafil Environmental Corrosion Service, Sales Bulletin 201, Purafil Inc., Doraville, GA (1989).
- 22 *ASHRAE Handbook*, Chap. 5: Fundamentals (1993).
- 23 KAKAC, S., SHAH, R.K., and AUNG, W., *Handbook of Single-Phase Convective Heat Transfer*, John Wiley & Sons, New York (1987).
- 24 International Energy Agency—Energy Conservation in Building and Community Systems—Sourcebook, Report Annex XIV: Condensation and Energy (1991).
- 25 FANTINI, L., and NANNEI, E., 'Analisi statistica della pressione parziale di vapore esterna della città di Genova' in *Proceedings 48th National Congress ATI (Associazione Termotecnica Italiana)*, Taormina (1993) 115–124.
- 26 ISETTI, C., and MAGRINI, A., 'Experimental determination of vapour transfer rates between moist air and a hygroscopic solution through a synthetic semi-permeable membrane' in *Indoor Air* (1995).

27 BEJAN, A., *Heat Transfer*, John Wiley & Sons, New York (1993).

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**Résumé**—*Ce papier décrit une nouvelle technique pour stabiliser l'humidité relative (HR) de l'air dans les vitrines de musées en employant une membrane synthétique hydrophobe couplée à une solution hygroscopique dans une membrane de contact. Les résultats du contrôle de HR pour deux vitrines identiques, l'une d'elles contrôlée par un dispositif muni d'une membrane de contact plane traversée par des courants d'air pulsé et une solution de LiCl, ont montré un effet stabilisateur significatif des variations de HR. Un modèle théorique permet de prévoir les résultats d'HR observés. Des calculs ultérieurs menés pendant un an ont montré qu'une stabilisation notable des variations de HR externe peut être obtenue avec une vitrine où de la circulation de l'air est limitée, une faible surface de la membrane et une petite quantité de solution par unité de volume de la vitrine. Il en résulte une discussion sur une solution analytique plus générale dans des conditions harmoniques.*

**Zusammenfassung**—*Eine neuartige Technik zur Stabilisierung der relativen Feuchte innerhalb von Museumsvitrinen nützt ein Membransystem in Verbindung mit einer hygroskopischen Flüssigkeit zur Filterung bzw. Konditionierung der in die Vitrine gelangenden Luft. Die Klimaaufzeichnungen zweier identischer Testvitrinen, von denen eine mit diesem System ausgerüstet war, zeigten deutlich stabilisierende Effekte dieser Einrichtung auf die Luftfeuchtigkeit innerhalb der Vitrine. Ein theoretisches Modell erlaubt Vorhersagen, die mit den gewonnenen Meßdaten in hohem Maße übereinstimmen. Berechnungen über die Zeitdauer eines Jahres zeigten, daß die durch die externe Luftfeuchtigkeit verursachten Schwankungen erheblich gesenkt werden können. Hierzu ist eine niedrige Luftdurchsatzrate nötig, eine kleine Membranfläche und eine geringe Flüssigkeitsmenge im Bezug zum Vitrinenvolumen. Die Verfasser entwickeln und diskutieren einen allgemeinen Lösungsansatz.*

**Resumen**—*En este artículo se presentan nuevas técnicas para estabilizar la humedad relativa (HR) del aire en el interior de las vitrinas de los museos, usando membranas sintéticas hidrofóbicas unido a solución higroscópica en una membrana de contacto. El control de los datos de HR para dos vitrinas idénticas, una controlada por una membrana de superficie plana a través de la cual fluye aire impulsado a través de una disolución de LiCl, muestra un significativo efecto de estabilización en las fluctuaciones de HR. Un modelo teórico permite predecir resultados muy cercanos a los observados en los datos prácticos obtenidos de la HR. Cálculos adicionales llevados a cabo en un periodo de un año, muestran que puede ser conseguida una notable estabilización de las variaciones externas de HR usando un nivel de baja circulación de aire, pequeña superficie de membrana y baja masa de disolución por volumen de la vitrina en cuestión. Se discute y plantea una solución general analítica en condiciones armónicas.*