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Published in:
I E E E Transactions on Components, Packaging and Manufacturing Technology

Link to article, DOI:
10.1109/TCPMT.2017.2655447

Publication date:
2017

Document Version
Peer reviewed version

This is the author's version of an article that has been published in this journal. Changes were made to this version by the publisher prior to publication.
The final version of record is available at http://dx.doi.org/10.1109/TCPMT.2017.2655447

Humidity build-up in electronic enclosures exposed to constant conditions

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***Abstract*— Electronic components and devices are exposed to a wide variety of climatic conditions, therefore the protection of electronic devices from humidity is becoming a critical factor in the system design. The ingress of moisture into typical electronic enclosures has been studied with defined parameters such as openings in the enclosure (drain holes, intentional openings or leak), and sealing and casing material. Related corrosion reliability issues due to humidity build-up have been evaluated using an interdigitated surface insulation resistance (SIR) pattern placed inside the enclosure during exposure. The moisture build-up inside the enclosure has been simulated using an equivalent RC circuit consisting of variables like controlled resistors and capacitors to describe the diffusivity, permeability, and storage in polymers.**

***Index Terms*— Electronic materials, electronic reliability, enclosures, humidity, moisture profile, temperature.**

I. INTRODUCTION

DESIGN of enclosures for electronics is an important aspect in controlling the humidity related reliability issues. The geometrical design of the enclosure could influence the response of interior humidity and local build-up to external fluctuations in the humidity and temperature. Uncontrolled humidity build-up in the device causes water film formation on sensitive parts such as printed circuit board assemblies (PCBAs), component surfaces, interconnects etc.[1]. Material combinations on the PCBA, contamination, applied bias, and water film cause leak current, electrochemical migration, and other corrosion failure modes [2-6]. Therefore, regulating the humidity transfer between exterior and interior of the device is an important factor in reducing the risk of humidity related failures in electronics.

In the past, the materials used for electronic enclosures were mainly metals. However, today polymers are used for different levels of packaging applications for electronics, including device enclosures. Polymers have several advantages over metals such as their light weight, ease of processing and assembly, better aesthetic design options, and cost-effectiveness [7]. Among the various available polymeric materials, polycarbonate (PC) provides the highest impact resistance or toughness. PC is an amorphous thermo-plastic material with excellent toughness, thermal stability, and it is a self-extinguishing material, which make it an ideal material for electronic enclosures. Polymeric materials with appropriate fillers are being used in order to maintain the mechanical integrity and shielding properties are not jeopardized. There are four choices regarding the use of polymeric materials for various applications namely: unfilled polymers, metal-filled polymers, intrinsically conductive polymers, and metalized polymers. The typical fillers used are based on stainless steels, nickel-plated graphite fibres, and titanium dioxide [7].

Providing compliance and weatherproofing to an electronic device are important aspects in enclosure design. The use of gaskets with polymeric materials helps to enhance the tightness between any lids or compartments to the bulk enclosure. However, the enclosure body needs to be designed in order to provide vents for cooling, input-output ports for electrical connections, hinges, screw locations etc. High degree of ingress protection according to the IP standard [8] and drain openings for letting out condensed water are conflicting design requirements. Drain openings must have diameters (lateral dimensions) in the range of 3 mm or higher in order to be effective, otherwise, surface tension effects may retain liquid water at the narrow passage. On the other hand, IP4X and higher class enclosures are without drain openings since no opening must allow a solid spherical object of 1 mm diameter to enter [9].

Humidity will tend to equilibrate between the outdoor climate and the interior of the electronic device. Water vapour diffusion and absorption are guided by the thermodynamic factors related to the concentration gradient namely the chemical potential difference. The diffusion can be between the areas with high water vapour content to low vapour content in the air or through a polymer material acting as diffusion medium. When flaws or openings exist in the wall of an enclosure separating different levels of humidity, moisture will diffuse through the opening [10]. A moisture-absorbing material will exchange water with the surrounding air until the relative concentration of moisture in the material equals to the relative humidity (RH) of the air [9], which is a function of the moisture permeability of the polymer material. Therefore, the use of polymer material for electronic enclosure increases the chance of moisture penetration due to the possibility of water molecules passing through the material and acting as a buffer for moisture content.

Literature focuses mainly on the moisture absorption by laminates, plastic, and mould compounds [11-19]. Although the effect of humidity on the properties of components [20-22] has been investigated, studies related to the humidity ingress into electronic enclosures are limited [23-24], while other works focus on temperature performance [25-26]. This paper focuses on understanding the effect of hole/vent size and water permeability through polymer enclosure material using experimental tests and RC circuit modelling [28-35] that implements the obtained experimental results. Effect of humidity build-up on corrosion reliability has been assessed using an interdigitated SIR PCB, while the RC circuit simulation evaluated the interior humidity response based on diffusivity, permeability, and solubility of the polymers. Results from the work are useful in predicting the interior humidity response in electronic enclosures.

II. MATERIALS AND METHODS

A. Electronic enclosures

The enclosures used for the experimental investigations were made of PC with dimensions 280 mm x 190 mm x 130 mm, and of aluminium (Al) with dimensions 260 mm x 160 mm x 90 mm. The gasket for the enclosures is made of polyurethane. The IP rating for the enclosure [8] is 66/67, which means that the enclosures assure a total protection against dust and a protection against strong jets of water or against the effect of immersion in water at a depth of 15 cm to 1 m. A through hole of different diameters has been drilled on one side of the enclosures in order to simulate a possible leakage opening (from cable feedthrough or sealing) or the presence of a drain hole. Enclosures with different polymeric casing materials and dimensions were investigated with the RC simulations.

B. Pressure test

The tightness of the IP class 66/67 enclosures has been tested initially using air pressure test, where either an over or under pressure of 100 mbar was applied inside the enclosure (corresponding to a temperature differential of ~ 30 ˚C). The decay or build-up of the internal pressure p(t) was constantly monitored and the time constant has been determined with the relation:

$$p(t) = p_0 \left(1 - e^{\frac{-t}{\tau}}\right) \quad (1)$$

where p_0 is the ambient pressure [bar], t is the time [s], and τ is the time constant for the internal pressure to reach the fraction $(1 - e^{-1}) = 0.63$ of the ambient value [s].

C. Internal climate investigation

The calibrated sensors were placed in the enclosures for monitoring the temperature and RH (PT1000 and HIH4021 sensors, Honeywell) (Figure 1). The sensors are connected to a data logging system (Model 2700 Multimeter, Keithley Instruments). The enclosures are exposed to constant temperature and RH in a climatic chamber (Espec, Escorp PL-3KPH). Prior to the experiments, the enclosures are kept inside the climatic chamber until the temperature and RH are constant. All experiments are started at 40% RH and then the RH inside the humidity chamber was increased up to 98% within 5 minutes.

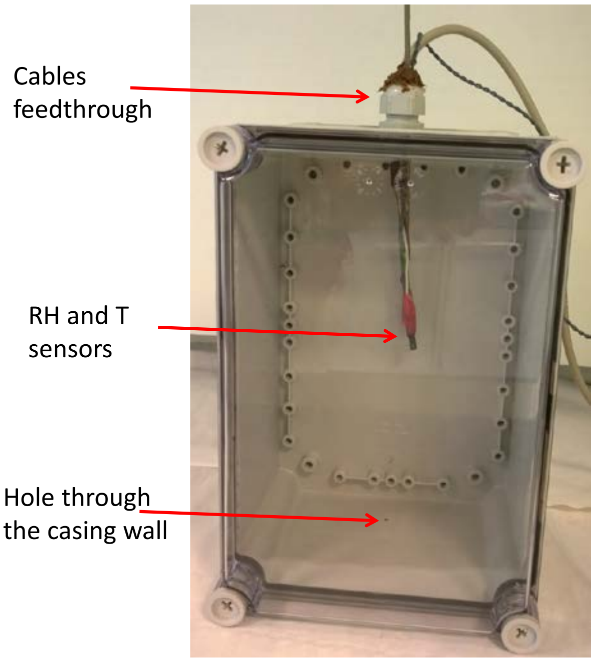

Fig. 1. Polycarbonate enclosure with RH and T sensors.

D. Sorption test

The moisture uptake of the PC material has been investigated in order to determine the diffusion, solubility, and permeability coefficients as well as the moisture saturation level of the materials. Samples of 3 mm thickness have been taken from the lid material (transparent PC) and from the body material (PC with TiO_2 fillers, grey colour) of the enclosure. The samples have been dried prior to the test at 125 ˚C for 24 hours and exposed to 25 ˚C and 60 ˚C at 98% RH, and the weight gain was measured using a calibrated precision electronic balance (0.1 mg), until the saturation plateau corresponding to a saturation level of moisture concentration (c_{sat}). The percentage weight gain *X* in [$_{wt.}$%] was calculated using the equation:

$$X(t) = \frac{\Delta m(t)}{m_0} \cdot 100 \qquad (2)$$

where m_0 [kg] is the initial weight of the sample and $\Delta m(t)$ is the change of weight of the sample [kg] after exposure for a time period *t*.

Considering the Fickian absorption, the diffusion coefficient of the bulk material *D* can be found from the slope of the initial linear part of the moisture uptake curve together with the sample weight at saturation state. The initial stage of moisture absorption ($m(t)/m_\infty < 0.5$) can be simplified as follows:

$$\frac{\Delta m(t)}{\Delta m_\infty} = 4\left(\frac{Dt}{\pi l^2}\right)^{1/2} \qquad (3)$$

where Δm_∞ is the change of weight at equilibrium [kg], *l* is the thickness of the material [m] and *D* is the diffusion coefficient [$m^2 \cdot s^{-1}$].

Henry's law of solubility states that a linear relationship exists between the external vapour pressure and the corresponding concentration within the surface of the material. The relationship is commonly extrapolated from a linear sorption isotherm. If one assumes the diffusion coefficient to be constant, the relationship between the diffusion coefficient, the permeation coefficient, and the solubility coefficient simplifies to:

$$P = D \cdot S \qquad (4)$$

$$S = \frac{\rho}{p_A} \cdot \frac{\Delta m_f}{m_0} \qquad (5)$$

where *P* is the permeation coefficient [$kg \cdot (m \cdot s.Pa)^{-1}$] and *S* is the solubility coefficient [$kg \cdot m^{-3}.Pa^{-1}$], ρ is the volumetric mass density [$kg.m^{-3}$] of the material, p_A is the partial water vapour pressure in ambient air [Pa], while Δm_f is the final change of weight of the sample [kg].

D. Leakage current (LC)

Effect of humidity build-up inside the enclosure on the functionality of the electronics is investigated by measuring the leakage current (LC) across a test interdigitated SIR PCB electrode pattern. The SIR PCB was made in accordance with IPC-4101/21 using FR4 substrate with dimensions of 168 mm × 112.4 mm and a thickness of 1.6 mm. The SIR electrodes are made of hot air solder levelled (HASL) surface finish (Sn/Ag/Cu solder alloy) and the pattern dimension was 13 mm × 25 mm with a pitch distance of 0.3 mm. The overlapping area was 10.8 mm in height and there were 41 sets of common overlap providing 442.8 mm as the total length of the opposing faces. The ratio of the total length of the opposing faces and the spacing of segments yields the nominal square count, which is 1476 for the pattern. For reference, the standard IPC-B-36 and IPC-B-24 comb patterns have 3538 and 1020 squares. The sensitivity of an SIR pattern increases with increasing number of squares. Detailed description of the test SIR PCB used for the testing can be found elsewhere [27]. A constant potential bias of 5 V DC was applied to the SIR pattern and the LC was measured constantly during the exposure test using a Biologic VSP-series potentiostat system. Prior to testing, the SIR patterns of

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the test boards were pre-contaminated with 15.6 $\mu g \cdot cm^{-2}$ of NaCl, and placed in the centre of the enclosures. The LC over the SIR was continuously measured during the enclosure exposure to 25 ˚C and 98% RH in the climatic chamber.

E. RC circuit simulation

Moisture response in any electronic system can be modelled using a RC approach [23; 28-35], which allows to predict humidity in any region of interest. The response of moisture is simulated by the use of an equivalent circuit consisting of multiple resistors (R) and capacitors (C), where the concentration of water vapour is represented by a voltage (electric potential difference). The RC approach has the capability to combine lumped components and discretized regions in 1D, 2D or 3D dimensionality, wherein the discretized regions can be based on finite volume method (FVM) discretization, for example. RC models would then allow the usage of any electronic circuit simulators like LTspice, Simetrix, Pspice, and Matlab [36].

Since the transport of moisture is investigated under isothermal conditions, moisture transport can be described by the Fick's second law and RC hygro circuit as described in the paper [28]. In order to model moisture inside an enclosure, a wall of enclosure was discretized into 3 elements based on 1D approach and the air-filled volume of the enclosure was considered as a lumped component, which is represented as the capacitance $C_{air} = V_{air}$ (Figure 2). Every wall element thus contained a combination of resistor and capacitor placed between two resistances. The diffusion resistance described the permeation of water vapour through the walls, while the capacitor was used to model the storage of water vapour. Here, the diffusion resistance (R) can be defined as [23, 34-35]:

$$R = \frac{l}{D \cdot A} \tag{6}$$

where l is the thickness of element [m], D is the diffusion coefficient [$m^2 \cdot s^{-1}$], A is the surface area of element [m^2]. Such combination was used for defining the time constant τ, which represents the time for the internal humidity inside enclosure to reach 63% of the ambient water vapour concentration value.

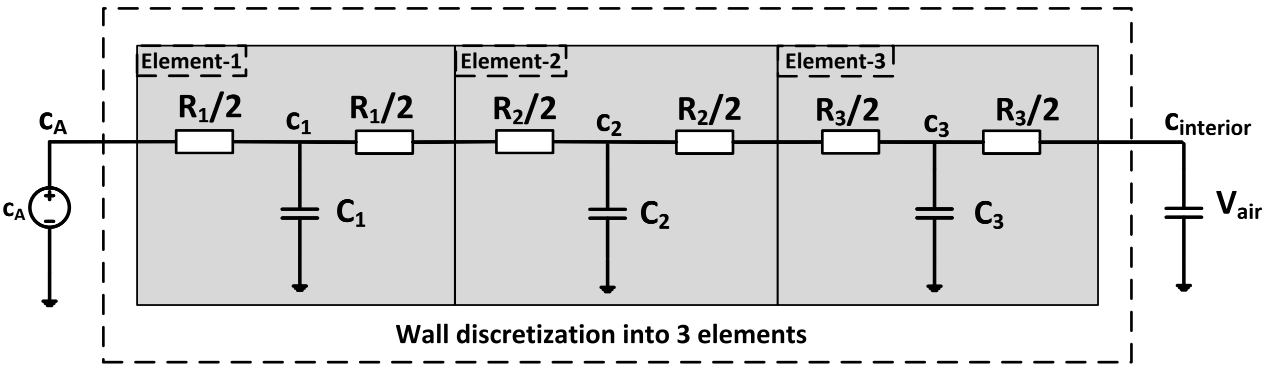

Fig. 2. Schematic of the RC circuit used for moisture modelling inside the enclosure.

The concentration of moisture is discontinuous at the environment-material or material-material interfaces [37]. Since, a voltage in RC circuit represents the humidity concentration; the voltage has to be equal at all capacitors or nodes when equilibrium is reached in the diffusion process. However, in the real conditions different materials have different concentration levels as illustrated in Figure 3. Therefore, modification is needed to make the RC hygro circuit applicable for moisture modelling through the air-material interface and it is broadly discussed by Bayerer et al. [28]. Fickian diffusion and Henry's law were applied, i.e. capacitance and resistance do not depend on concentration and all parameters like solubility and diffusivity are temperature dependent.

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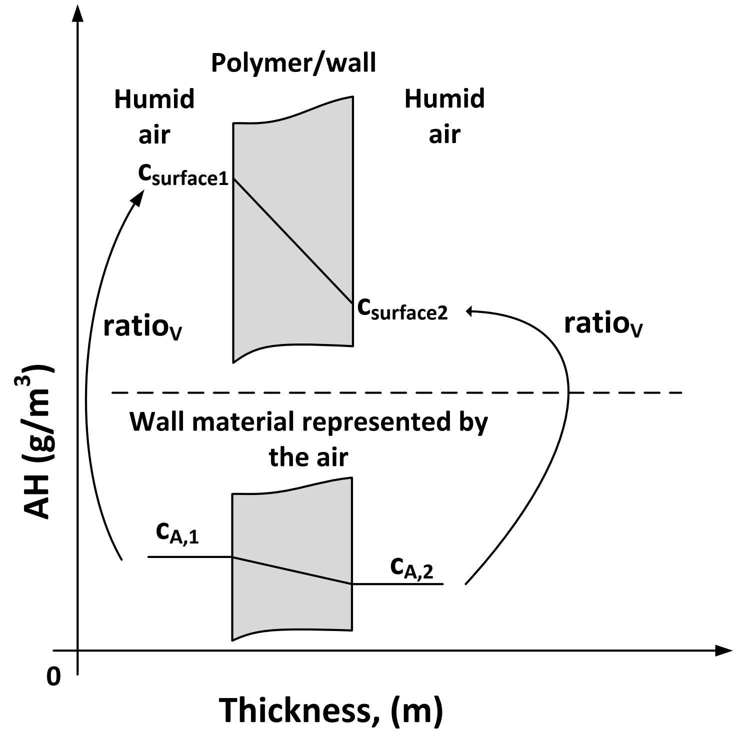

Fig. 3. Schematic of the discontinuous moisture concentration at the environment-material interface.

Thus, the actual volume or the capacitance needs to be transformed to the equivalent air capacitance using equations (7-9).

$$V_{equivalent} = \frac{\Delta m(t)}{c_A} = \frac{S(T) \cdot p_A \cdot V_{polymer}}{c_A} \quad (7)$$

$$ratio_V = S(T) \cdot \frac{p_A}{c_A} \quad (8)$$

$$C = V_{equivalent} = V_{polymer} \cdot ratio_V \quad (9)$$

where: $V_{equivalent}$ is the equivalent air volume for the transformed material [m^3], c_A is the water vapour concentration in ambient air [kg·m^{-3}], $S(T)$ is the temperature dependent solubility of water in polymer [kg·m^{-3}·Pa^{-1}], $V_{polymer}$ is the geometric volume of polymer [m^3], C is the capacitance representing moisture storage in any material or discretized element [m^3], $ratio_V$ is the dimensionless transformation factor relating solubility multiplied by actual water vapour pressure or water vapour concentration in the polymer and water vapour concentration in air (reference material).

From the equation 9, it can be seen that $ratio_V$ defines the relation between the actual and the equivalent volumes of any discretized element. The $ratio_V$ is defined as ratio between the solubility at actual vapour pressure and actual concentration of vapour in the air. Resistors representing the diffusion also need to be transformed to the equivalent air resistance in order to avoid discontinuity. Thus, either lumped component or each segment of air and material has to be transformed, and the equation 6 of diffusion resistance should be divided by $ratio_V$:

$$R_{diff\ equivalent} = \frac{l}{D \cdot A \cdot ratio_V} \quad (10)$$

After modification, the concentration gradient across the wall is larger in the solid material (between $c_{surface1}$ and $c_{surface2}$) than in the air (between ambient water vapour concentrations in the air $c_{A,1}$ and $c_{A,2}$) (Figure 3). Thus, to gain the same amount of water penetrating the wall, the resistance (*R*) has to be reduced as well (as shown in the equation 10). After all transformations, the RC circuit was modelled using LTspice software [38] and the electrical circuit in Figure 1 was applied for all modelling work reported in this paper. The good agreement between results obtained from the generated RC model simulation, and the experiments performed with the PC enclosures has given a good confidence for extending the model to simulate humidity build-up in enclosures of different volumes and with different casing materials, based on diffusion and solubility coefficients found experimentally.

III. RESULTS

A. *Pressure leak test of the enclosures*

The results showed that the as-received enclosures are very tight with a time constant of the order of 4.6 weeks. Since the humidity build-up studies involve the use of humidity and temperature sensors connected through cables, an additional leak test experiment was conducted using the enclosures with the presence of cable feedthrough. The test was carried out with a metal rod inside the feedthrough and with one or two sensor cables. Due to the presence of the feedthrough, the time constant for pressure drop has been reduced to 6 min, which is equivalent to a hole size of ~0.4 mm diameter. Further, in presence of the feedthrough together with one or two sensor cables, the time constant has been reduced to 2 and 1 min respectively.

B. *Humidity build-up inside the enclosure under constant external humidity*

1) *Effect of hole size and geometry*

The PC enclosures with different hole sizes have been exposed to constant conditions of 25 ˚C / 98% RH and 60 ˚C / 98% RH, and the ingress of humidity has been measured as shown in Figure 4. In all the cases, the humidity build-up in the enclosure is faster with increase in hole size. With a 10 mm hole, the profile showed an immediate build-up of humidity to the saturated level. Test at 60 ˚C showed faster build-up of humidity compared to the test at 25 ˚C. Under both temperature conditions, the presence of Gore vent to the enclosure gave a humidity ingress rate similar to an enclosure with a hole size lower or close to 1 mm. Enclosures with no hole also showed humidity build up, however slower than compared to the test with 1 mm hole size. This might be equivalent to the ~0.4 mm hole size determined for the closed enclosure under pressure test.

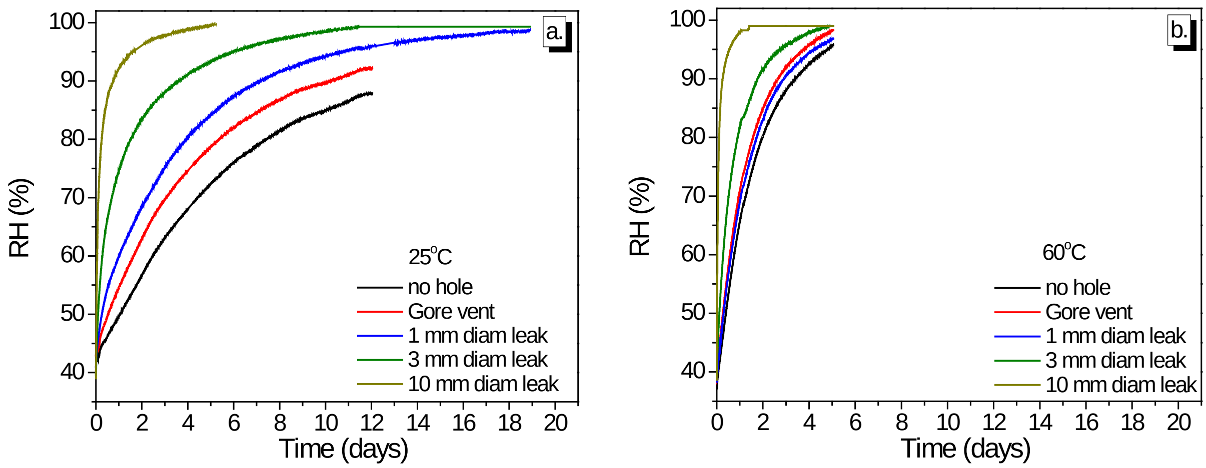

Fig. 4. Effect of hole size on the internal humidity build up in the PC enclosures exposed to 98% RH: a) 25 ˚C and b) 60 ˚C.

Knowing the diffusivity of water vapour, the time constant τ can be calculated using the following equation (Tencer et al. [23]).

$$\tau = \frac{V \cdot l}{A \cdot D} \tag{11}$$

where *V* is the internal volume [$6.25 \cdot 10^{-3}$ m^3], *l* is the thickness of the hole [$2.2 \cdot 10^{-3}$ m], *A* is the area of the hole [0, 0.78, 7.1 and 78.5 10^{-6} m^2], and *D* is the diffusion of water vapour at 1 atm and at given temperature [$24 \cdot 10^{-6}$ $m^2 \cdot s^{-1}$ (at

25 ˚C) and $31 \cdot 10^{-6}$ $m^2 \cdot s^{-1}$ (at 60 ˚C)]. Table 1 shows the time constants determined from the experimental data in Figure 4 as well as the calculated time constants using equation 11.

TABLE I
EXPERIMENTAL AND CALCULATED TIME CONSTANTS RELATED TO HUMIDITY BUILD UP

Hole diameter (mm)	Time constant (days) (calculated)	Time constant (days) (from experiment)	Time constant (days) (calculated)	Time constant (days) (from experiment)
	25 ˚C		60 ˚C	
0	/	6.72	/	1.80
Gore	/	4.81	/	1.58
1	8.63	3.47	6.67	1.57
3	0.96	1.22	0.74	0.80
10	0.09	0.19	0.07	0.09

The time constants from experimental data are significantly lower than the calculated values, especially in the case of 1 mm hole (difference around 5 days). This shows that in addition to the equivalent hole size of ~ 0.4 mm diameter, other mechanisms such as diffusion through the PC wall is occurring during testing and has to be taken in consideration for the calculation of the time constant. The time constant for humidity ingress into the enclosure with 10 mm hole diameter is close to an open enclosure with a time constant of 4.5 hours and 2.2 hours at 25 ˚C and 60 ˚C respectively.

Figure 5 shows the effect of hole thickness (changed by attaching tubes) on the humidity build-up. Results show that the humidity ingress into the enclosures with an opening of 2 mm diameter with a tube length of 2.5 and 5 cm is similar to the moisture ingress without opening (black curve). In these two cases, the diffusion through the PC walls has been the dominant mechanism for moisture ingress, while the resistances of the tubes were too high. A bigger opening diameter of 3 mm and 5 cm tube length has shortened the time constant from 6.7 to 4.9 days.

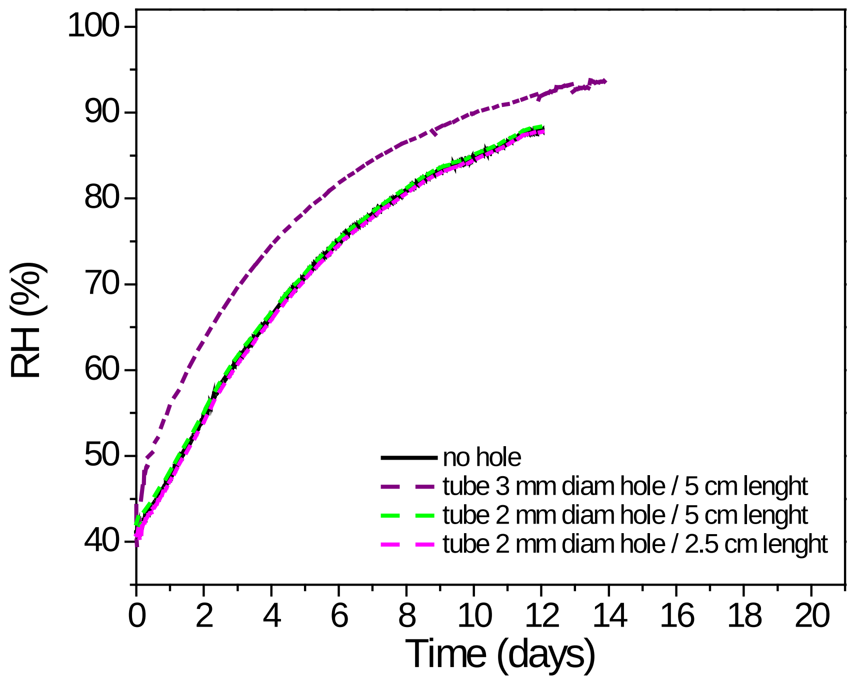

Fig. 5. Effect of hole geometry on the internal humidity build up in the PC enclosures exposed to 25 ˚C and 98% RH.

2) Moisture diffusion through the PC casing

Effect of sealing on humidity build-up

In order to determine the level of moisture ingress into the PC enclosure without an intentional hole and unintentional openings (due to the gasket or cable feedthrough), an additional test was conducted by sealing all parts of the enclosure with a silicone sealant. Results of the test are shown in Figure 6 with various conditions of sealing. Overall the result shows that the perfect sealing has resulted in a slight reduction in moisture build-up, however still the profiles showed slow humidity build-up with time indicating moisture diffusion through walls of the enclosure. Sealing around the cable feedthrough did not show any effect showing that the contribution from this to the humidity build up is negligible. Test using 2 mm hole size with and without sealing of the sensor cables also showed similar results.

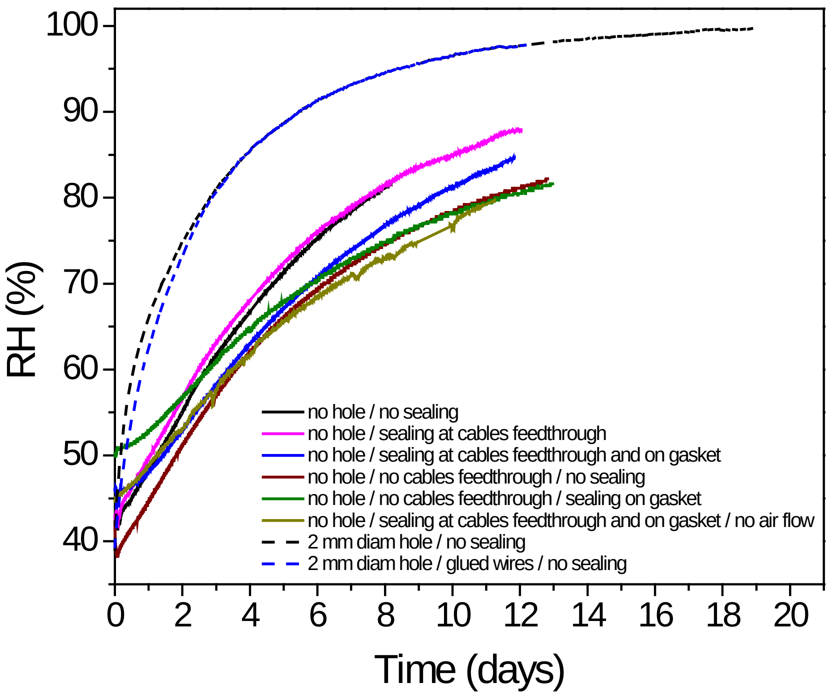

Fig. 6. Effect of sealing around the enclosure and cable through area on the internal humidity build up in the PC enclosures exposed to 25 ˚C and 98% RH.

Investigation of moisture absorption by PC

Experimental test of moisture absorption into the PC materials (from the lid material (transparent PC) and from the body material (PC with TiO_2 fillers, grey colour)) has been carried out and Figure 7 shows the moisture uptake profile for both types of the PC materials. Profiles show that the moisture absorption by PC is considerably fast, especially at 60 ˚C. The time to reach the saturation was about 5 days at 25 ˚C and 1 day at 60 ˚C.

Using the experimental data, diffusion, solubility, and permeability coefficients have been deduced as shown in Table 2. The diffusion coefficient at 60 ˚C is ~ 5 times higher than the diffusion coefficient at 25 ˚C, while the saturation value of concentration (c_{sat}) is ~ 1.2 times higher. The presence of the TiO_2 fillers has decreased the saturated level of moisture concentration (c_{sat}). However, the permeability values are higher for the PC with fillers.

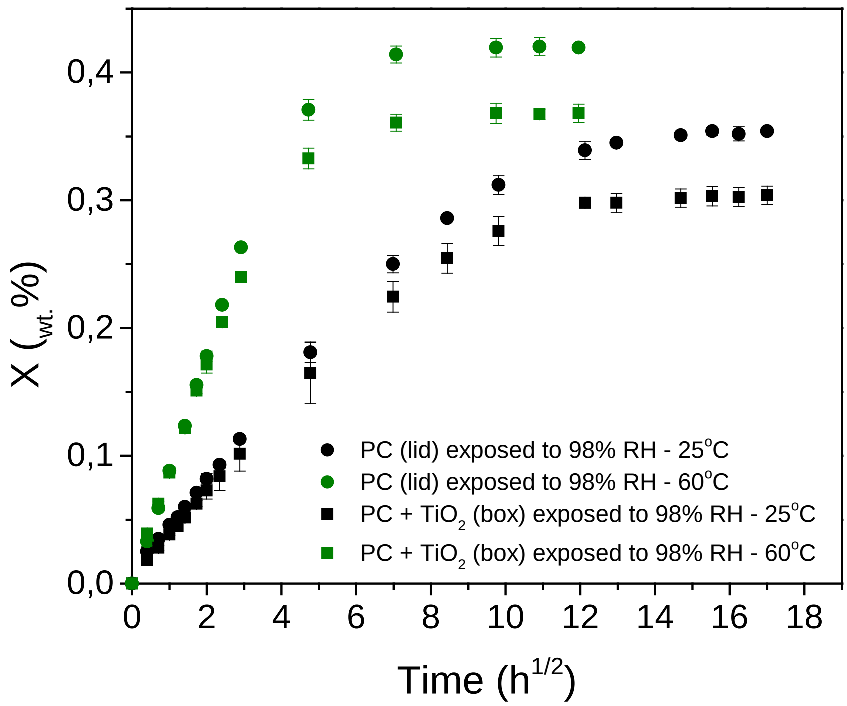

Fig. 7. Moisture absorption profile for PC material using weight gain measurement.

TABLE II
DIFFUSION, SOLUBILITY AND PERMEABILITY COEFFICIENT OF THE PC CASING MATERIAL

Material	Temperature [˚C]	D [10^{-12} $m^2 \cdot s^{-1}$]	S [10^{-3} $kg \cdot m^{-3} \cdot Pa^{-1}$]	P [10^{-15} $kg.m^{-1}.s^{-1} \cdot Pa^{-1}$]	c_{sat} [$_{wt}$.%]
PC transparent	25 ˚C	3.65	1.33	4.83	0.35
PC + TiO2 filler		4.51	1.30	5.87	0.30
PC transparent	60 ˚C	17.95	0.27	4.80	0.42
PC + TiO2 filler		23.44	0.24	5.70	0.37

3) Comparison of moisture ingress in polycarbonate and aluminium enclosures

Figure 8 shows the humidity build-up in an Al enclosure in comparison to a PC enclosure. No hole in both cases means tightly closed, however the tightness corresponds to an equivalent leak size of 0.4 mm due to the cables feedthrough and sealing around the enclosure. The test is carried out to understand the effect of PC material in assisting diffusion through the walls in moisture build-up. Since the volume of the enclosures is not similar, a normalised plot has been chosen and the represented moisture ingress is therefore identical for different volumes of enclosures. Profiles show that the ingress of moisture into the Al enclosure is significantly slow without hole, while the difference decreases with increasing hole size. In the case of no hole, the only pathway for moisture ingress is through any leak in the case of Al enclosure, where no diffusion through the wall can be expected.

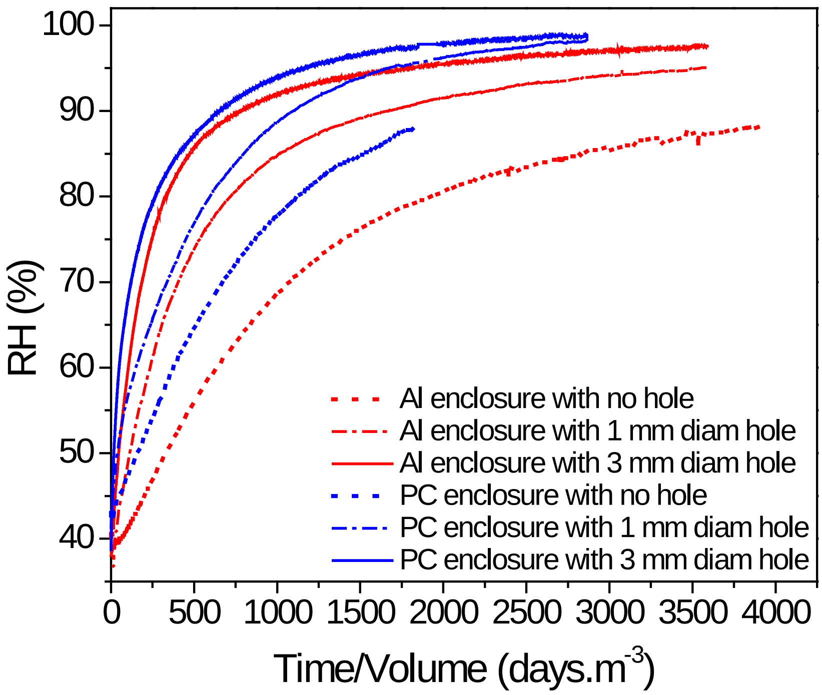

Fig. 8. Comparison of moisture ingress into PC and Al enclosures at 25 ˚C.

4) Leak current response with humidity build up inside PC enclosures

Figure 9 shows the leak current response on the contaminated SIR comb pattern due to humidity build-up inside the enclosure as a function of hole size. The critical relative humidity (cRH) for NaCl is about 70-75% RH at 25 ˚C, therefore current values were lower initially when the humidity was below 70% RH. However, at humidity levels higher that 70% RH, deliquescence occurs, and the leak current showed higher current levels and signs of electrochemical migration (sudden jump in current). The time needed for this varies from 1-3 days depending on the hole sizes due to different levels of humidity build up.

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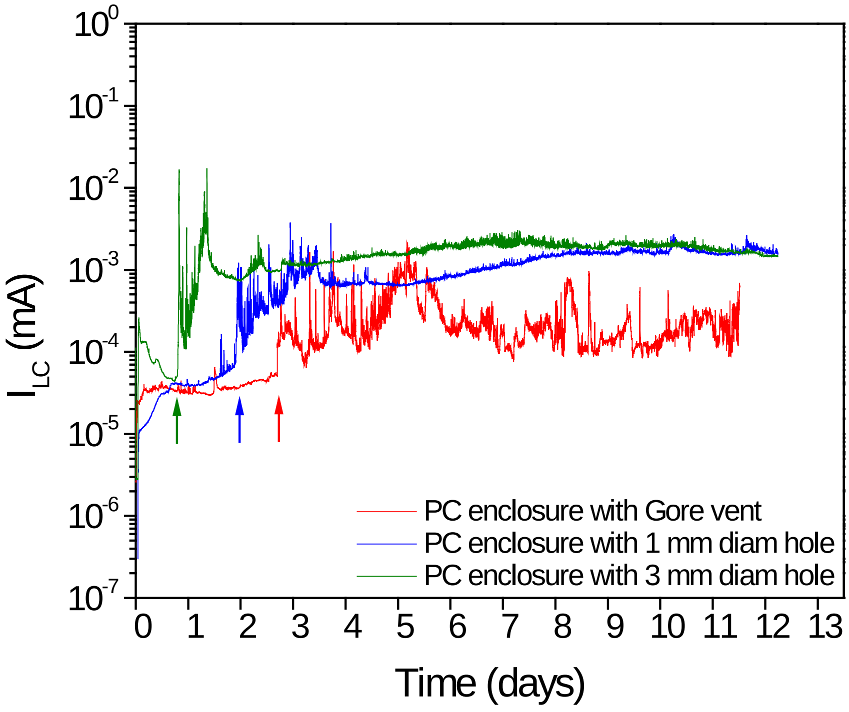

Fig. 9. Effect of hole size and build-up of humidity on LC of SIR comb pattern pre-contaminated with 15.6 µg·cm-2 of NaCl (applied voltage: 5 V DC).

C. Effect of moisture uptake by the casing material on humidity build up in the enclosure

1) Calculation using experimental data

Using the solubility parameter related to the PC material as well as the volume of the enclosure, the relative effect of moisture absorption by the PC material on internal humidity build-up of the enclosure can be calculated. The ability to hold moisture by the casing walls (A) (at saturated condition) can be calculated by:

$$A = m \cdot c_{sat} \qquad (12)$$

While the ability to hold moisture inside the internal volume of enclosure (B) (at saturated condition) can be calculated by:

$$B = V_{int} \cdot d_{wv} \qquad (13)$$

where m is the mass of the casing material [kg], c_{sat} is the saturation level of moisture concentration of the PC (values found experimentally as shown in Table 2) [$_{wt.}$%], V_{int} is the internal volume of the enclosure [m^3], and d_{wv} is the density of saturated water vapour [0.023 $kg \cdot m^{-3}$ at 25 ˚C and 0.130 $kg \cdot m^{-3}$ at 60 ˚C]. The thickness of the casing wall considered in this example is 3 mm.

In Table 3, the ratio A/B shows the relative amount of moisture possible to be held by the casing wall in comparison to the amount of water needed for saturation inside the volume of the enclosure. The calculation shows that depending on the size of the enclosure, the moisture release from the casing walls can be significant in enhancing the moisture build-up inside the enclosure. This means once the system is saturated, not only the diffusion through the casing is important, but also important is the ability of the casing to hold and release moisture into the interior depending on the conditions inside.

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TABLE III
IMPORTANCE OF AMOUNT OF WATER IN PC WALLS OF 3 MM THICKNESS COMPARED TO THE AMOUNT OF WATER VAPOUR THE ENCLOSURE COULD HOLD DEPENDING ON THE ENCLOSURE DIMENSIONS

Case	Volume enclosure			A/B (25 ˚C)	A/B (60 ˚C)
	L (mm)	l (mm)	h (mm)		
1	28	19	13	296	63
2	140	95	65	40	8
3	280	190	130	19	4
4	1400	950	650	3.7	0.8
5	2800	1900	1300	1.8	0.4
6	14000	9500	6500	0.4	0.1

In order to illustrate this, an experiment was conducted using PC and Al enclosures, where the humidity release after the saturation has been studied. The enclosures were exposed to 25 ˚C and 98% RH for 5 days to fully saturate the casing material. Following this the enclosure is opened to equilibrate the RH with outdoor conditions (~ 60% RH) and closed again. After closing, the increase of humidity inside the enclosures due to release from the saturated wall is then monitored.

Immediately after closing the lid (Figure 10), the humidity level increased inside the enclosures depending on the volume of the enclosure and material. For the PC enclosures, the humidity level reached 91-95% RH, while for the Al enclosure, the level remind at 85% RH. In all the cases, the humidity with time decreased due to the possible leak from the enclosures (external condition was T = 25 ˚C and RH = 60% RH). However compared to the Al enclosure, the PC enclosures kept high levels of humidity significantly longer time than for Al enclosures, which was also a function of the volume of the enclosure.

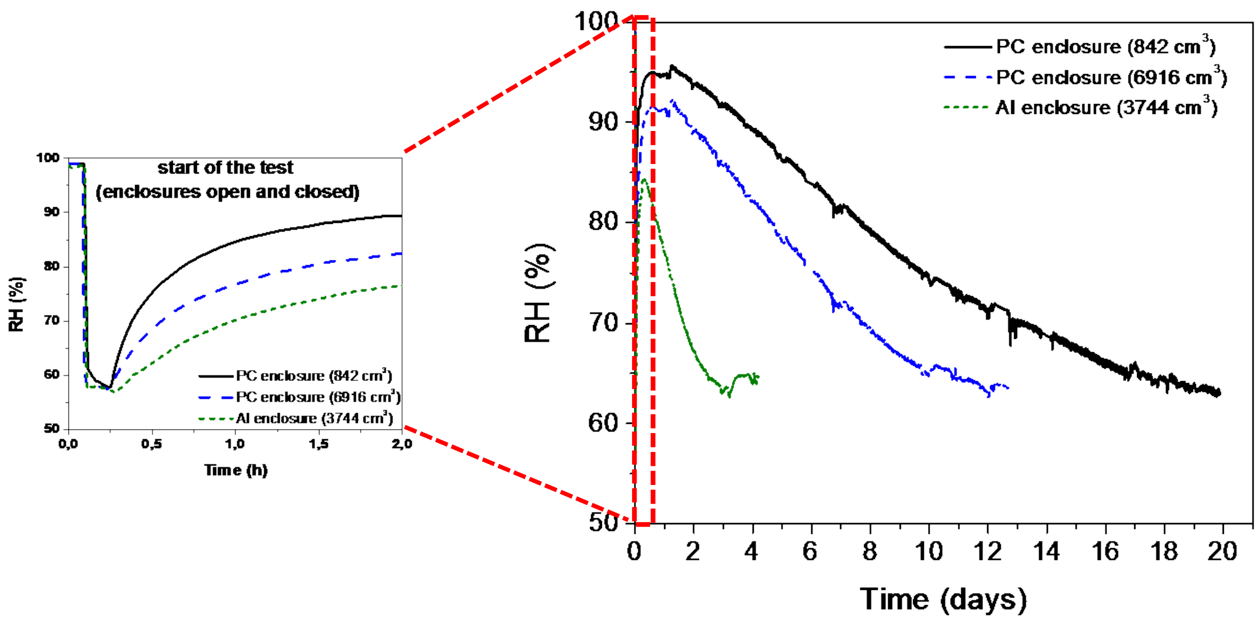

Fig. 10. Effect of moisture release from casing walls of enclosure on internal humidity.

Figure 11 shows the effect of the presence of condensation (liquid water) inside the enclosures. The enclosures have been exposed to 60 ˚C and 98% RH during 3 days to fully saturate the casing material, and then the enclosures have been exposed to room conditions (25 ˚C and 60% RH). The AH at 60 ˚C and 98% RH is 127 g·m^{-3}, while it is reduced to 23 g·m^{-3} at 25 ˚C. During the cooling, the excess moisture has condensed inside the enclosures, while the RH value has reached 100% RH in all cases. The presence of liquid water (indicated by the presence of constant 100% RH) remained for 7 days in the PC enclosures with no hole, while for 6.8, 4.6 and 3.8 days for the PC enclosures with 1 mm diameter hole, with a Gore vent, and with 3 mm diameter hole respectively. The PC enclosure with smaller volume contained liquid water during longer time, almost for 7.4 days, while the Al enclosure contained also liquid water up to 5.7 days, but the internal moisture has decreased very slowly in this case as there was no diffusion through the walls.

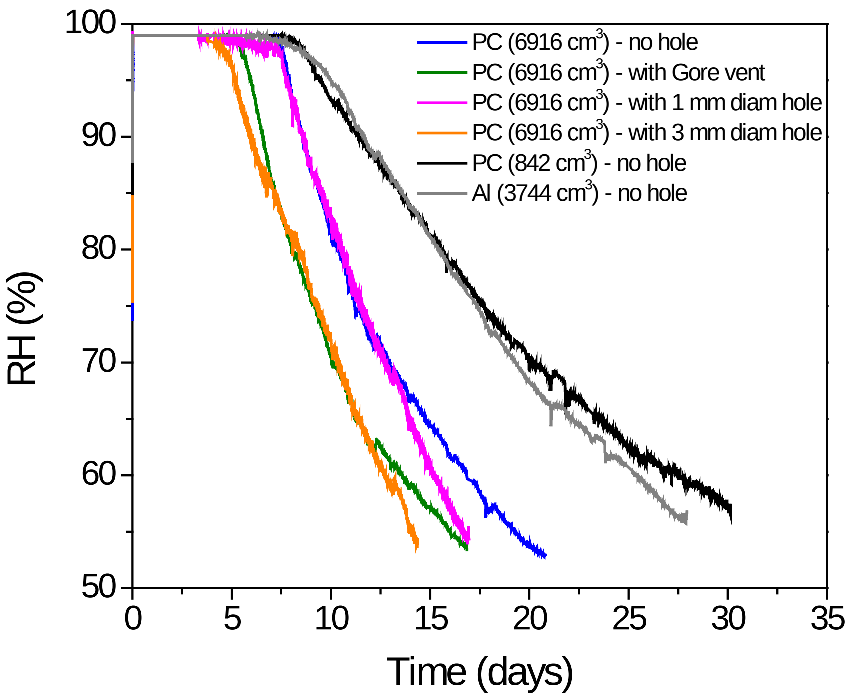

Fig. 11. Effect of presence of condensation and moisture diffusion through walls on internal humidity of enclosures.

2) *Simulation of humidity build up using RC circuit modelling*

The developed RC simulation has modelled the effect of the moisture release from the PC casing walls on internal humidity build-up in enclosures with specific volumes listed in Table 3. The conditions for the simulation are a temperature of 25 ˚C, a RH of 40% outside and inside the enclosure, the casing wall of the enclosure is saturated with moisture (containing 0.32 wt.% of moisture), and the diffusion coefficient of PC is $4.5 \cdot 10^{-12}$ m^2·s^{-1} (25 °C). The moisture absorption of the PC walls has been calculated based on equation 14:

$$X = \frac{\Delta m_f}{m_0} \cdot 100\% = \frac{c_{sat}}{\rho} \cdot 100\% \quad (14)$$

where c_{sat} is the saturation level of moisture concentration [4.16 kg·m^{-3} at 25 ˚C], and ρ is the density of PC material [1300 kg·m^{-3}].

As shown in Table 3, in case 1, at 25 ˚C, the PC casing walls can hold roughly 300 times more water than the internal volume, while the ratio is almost 0 for case 6. Figure 12 shows clearly that the release of moisture from the PC walls in case 1 has increased the internal humidity level up to 100% RH, while in case 6, the RH level has barely reached only 50% RH, showing good agreement with experimental results.

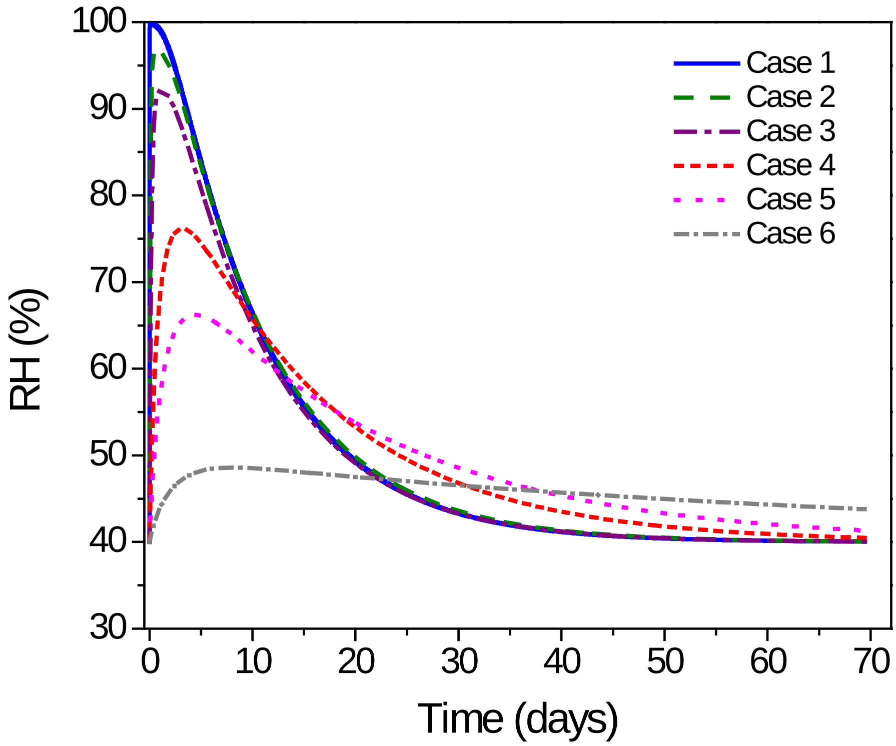

Fig. 12. Simulation of the effect of moisture release from PC walls on the internal humidity build up in the enclosures with different volumes (listed in Table 3) exposed to 25 ˚C.

Figure 13 shows the large range of diffusion, solubility and permeability coefficients at 60 ˚C of commercially available thermoplastic materials used in electronic enclosures, namely materials A, B, C, D and E (confidential data [39]), and PC.

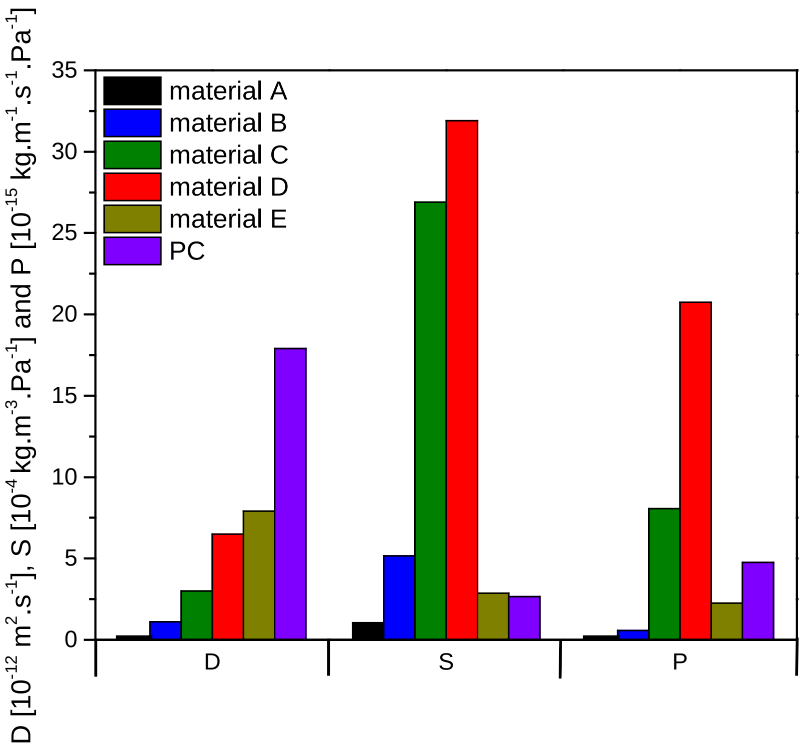

Fig. 13. Diffusion, solubility, and permeability coefficients at 60 ˚C of different polymer enclosure materials.

The developed RC simulation has modelled the moisture ingress into the enclosures made of different polymers exposed to 60 ˚C and 98% RH (Figure 14), and the effect of the moisture release from the different saturated polymer casing walls on internal humidity build-up in the enclosures, at 60 ˚C, with a relative humidity of 40% RH outside and inside the enclosure (Figure 15). The specific volume of the enclosures is 6916 cm^3, the wall thickness is 3 mm, and the diffusion, solubility and permeability parameters are extracted from Figure 13, and equations 8 and 9 have been used for the calculation.

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The final version of record is available at http://dx.doi.org/10.1109/TCPMT.2017.2655447

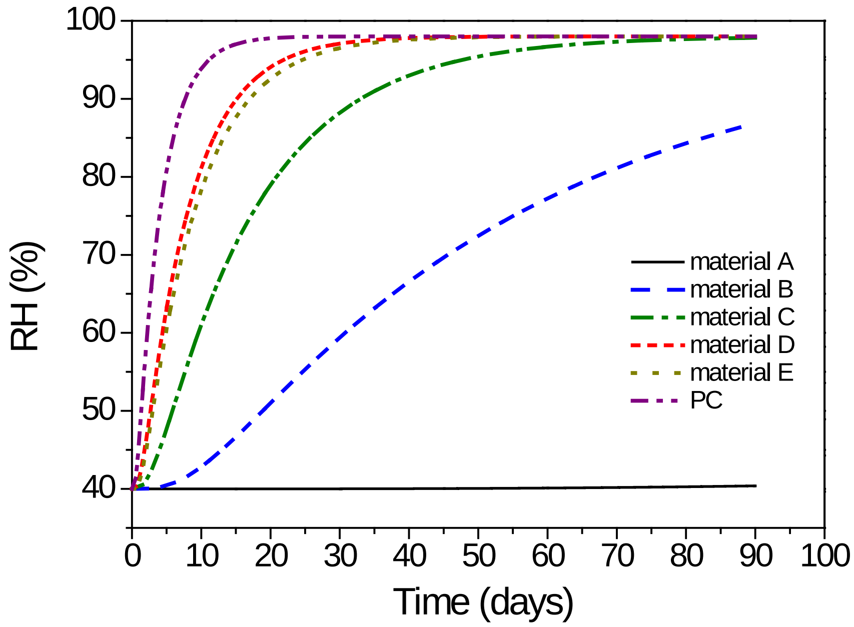

Fig. 14. RC simulation of the effect of different types of polymer walls on the internal humidity build up in the enclosures exposed to 60 ˚C and 98% RH.

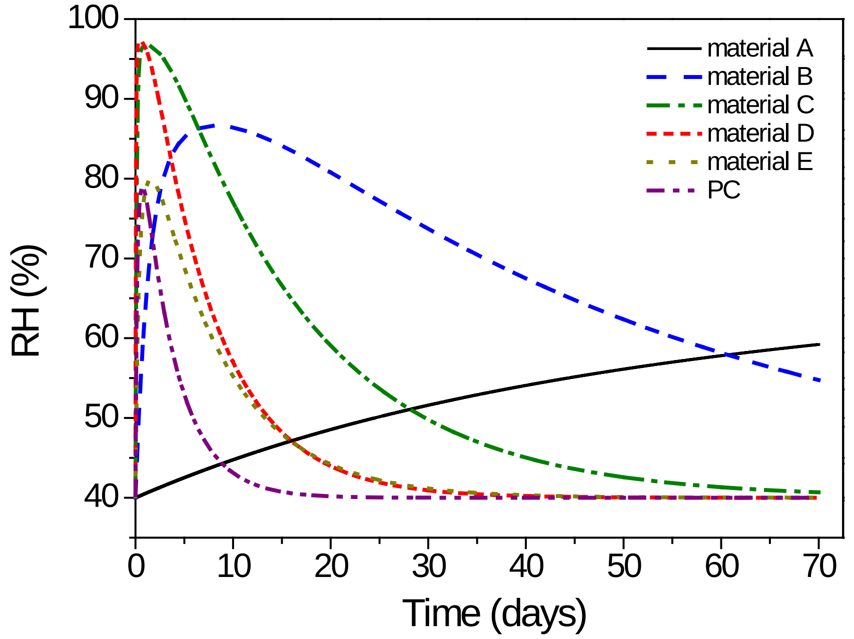

Fig. 15. RC simulation of the effect of moisture release of different types of polymer walls on the internal humidity build up in the enclosures exposed to 60 ˚C.

While the internal humidity has barely increased of 0.4% RH inside the enclosure made of material A after 90 days of exposure to 98% RH due to its low diffusion coefficient, the time constants to reach 63% of the outdoor condition are respectively 59.5, 18.5, 8.5, 9.5, and 4.3 days for the enclosures made in materials B, C, D, E and PC (Figure 14). The large range of diffusion and solubility coefficients of the polymers has also led to different profiles of internal humidity build-up due to the moisture release of the polymer walls. Figure 15 shows that the relatively low solubility coefficient of the PC walls has indeed increased the internal RH up to 79% RH, but the relative high diffusion coefficient of the PC walls has allowed the internal humidity to diffuse towards the lower RH outdoor air. Therefore, the internal humidity has been reduced to 40% RH after around 15 days. In the case of material C walls, the relative solubility coefficient is high, while its relative diffusion coefficient is low. The internal RH has reached 97% RH, while it took around 65 days to reduce it to 40% RH.

IV. Discussion

A large number of electronic devices are exposed to environments with no climate control, and different types of enclosures are used in electronics varying in size, geometry, and material. The main casing materials used today are PC and Al, or a combination of them. In addition, most of the enclosures are not perfectly sealed, and consequently are permeable to water through slight leak through some parts of the enclosure or through intentional hole (example drain hole) as part of the enclosure. The humidity build-up inside the device will lead to electrical issues and corrosion on the electronics [40-42] due to the electrochemical process resulting from the water film connecting closely spaced metallic parts under potential bias [43-45]. It is important to predict sufficient internal conditions, at the known climatic conditions, in order to keep both the air inside the enclosure at low RH and the surface temperature of the PCBA higher than the dew point temperature [1]. The level of contaminations on the PCBA surfaces is also a critical factor regarding the moisture adsorption and the formation of an electrolyte solution, which can lead to electronic failures even at low RH level.

When exposed to cycling conditions, the ingress of water by breathing effect is the most important phenomena. But when exposed to constant conditions, with high level of humidity in the surrounding air, the ingress of water by diffusion becomes the most important mechanism. Diffusion of water molecules through the material or opening will be proportional to the difference in absolute concentration of water (AH) outside and inside. The level of entry of moisture will be governed by the openings in enclosures (through drain hole, other intentional openings, or leak) and diffusion through sealing or walls of the enclosure if it is made by polymer.

Results of moisture ingress into the PC enclosures (volume: 6916 cm^3) exposed to constant climatic conditions (to 25 and 60 ˚C at 98% RH) show relative importance of the opening and permeation though the wall in building-up internal humidity levels. The time constant τ, representing the time to reach 63% of the outdoor RH condition, showed clear influence of these two parameters. The fast moisture ingress into the enclosure with a 10 mm hole (Figure 4) showed that it can be considered as an open enclosure, in which the humidity will equilibrate in short time with the outdoor conditions (τ = 4.5 and 2 h at 25 and 60 ˚C). The time constant for moisture equilibration in the case of an opening of 3 mm is up to 29 and 19 h at the two temperatures, while 1 mm hole or Gore vent showed τ values in the order of days (3.5 - 4.8 days at 25 ˚C and ~1.6 days at 60 ˚C). Gore vents are meant to secure dry enclosures, but for moisture its behaviour is close to having 1 mm hole, they are not vapour barriers; they aim to equalize pressure between the inside and outside of the enclosure. The experiments show that moisture exchange was allowed between the enclosure and the outside through the diffusion of water vapour. Gore vents can only repel liquid water from coming in, but also for going out, therefore they cannot replace drain hole. This means that the function of a Gore-vent is only a relatively well-defined breathing and diffusion path through the enclosure [9]. In all cases, the ingress of moisture was faster than expected for PC (even after considering the leak of 0.4 mm based on tightness testing) according to the time constant calculation using the equation from Tencer et al. [23]. Further experiments with sealing around the gasket and the cables feedthrough (Figure 6) did not show any relevant change in humidity ingress into the enclosures showing that the preferential pathway for moisture ingress under these conditions was mainly through the PC walls. Sorption test (Figure 7) showed that the time to saturate a PC material of 3 mm thickness is about 5 days at 25 ˚C and 1 day at 60 ˚C, which is relatively short compared to the time scale of the humidity ingress reported in Figure 4 for various openings. The diffusion coefficient of PC material (Table 2) is $4.5\cdot10^{-12}$ $m^2\cdot s^{-1}$ and $23.4\cdot10^{-12}$ $m^2\cdot s^{-1}$ at 25 ˚C and 60 ˚C, and accordingly, the time constant for the moisture ingress into the closed enclosure at 60 ˚C is around 4 times less than the time constant at 25 ˚C (Table 1).

Overall, the results show that the humidity build-up in PC enclosures compared to the Al enclosures is significantly affected by the diffusion through the PC material. The effect is noticeable especially for lower hole sizes and openings via tubes irrespective of the temperature. By knowing diffusion parameters for applied polymers, the ingress rate can be calculated and hence the enclosure can be dimensioned to reduce climatic issues during life time [9], providing calculations and tests showing that low internal RH is guaranteed within the device's lifetime [34]. Plastic materials are all permeable to water, even in perfect void-free condition. Water transport properties of various types of polymers used for electronic enclosure differ enormously (Figure 13). In moisture-critical situations, it is absolutely essential to know the materials properties and to choose the right material.

The storage of moisture inside electronic enclosure is determined by the solubility of moisture in polymers, and moisture can also be stored on the surfaces of the internal walls [28]. When the concentration of moisture in air reaches the saturation level, condensation takes place, and the RH will reach 100%. Then, the condensed water will evaporate when the level of humidity falls below the saturation level. This could significantly affect the humidity build up inside the enclosure made of polymers as shown in Figures 10 and 11, which show that either under humid or condensing conditions, the solubility and the diffusion of moisture into the internal walls could highly influence the humidity build up. In both cases, the volume of the enclosure and the presence of opening play a large role. While opening allowed a faster moisture diffusion and a faster equilibrium with outdoor conditions (and consequently a faster evaporation of condensed water), the release of moisture from the wall has increased the internal RH of small enclosures considerably. Table 4 shows the ability of the enclosure walls vs. the ability of the enclosure interior volume to hold water. It can be seen that in some cases polymer walls can contain large amounts of water compared to the air volume inside the enclosure.

A RC approach allowed modelling the effect of the volume and the type of polymer of the casing wall on the moisture ingress and on the moisture release from the walls. Considering a same wall thickness (3 mm), it can be observed (Figure 12) that RH has reached 100% in the case of moisture release from PC walls of enclosures of 7, 900, and 7000 cm^3, while only an increase of 10% RH was observed in the case of bigger volume (1.7 m^3) at 25 ˚C. This is in agreement with experimental observations. The developed RC model has also shown the effect of the water transport properties of different polymers used in electronic enclosures. While the diffusion coefficient is the main parameter regarding the moisture transfer for equilibrium between indoor and outdoor climates, the ability of the polymer to store water (related to the solubility coefficient) is important in the case of temperature or RH change in the surrounding environment during which water release from the wall inside the enclosure is happening [9;28]. The 1D RC modelling has found to be an excellent tool to predict such processes, which convenient and simple to use without rigorous fluid flow modelling. Such models can also allow simulating complex climate profiles within minutes [28].

Figure 9 shows the effect of hole size and related ECM due to humidity ingress inside the enclosures. When the level of 70-75% RH is reached, which corresponds to the deliquescence point of NaCl, a sudden increase of current is observed. The drop in surface insulation resistance due to deliquescence caused higher leak current, which eventually led to electrochemical migration on the SIR PCB. The level and type of contamination left on the surface of a PCBA [46] will determine the threshold of humidity at which electronic failures may occur, and then represents the safe humidity level to be maintained in the electronic enclosure. The sources of contaminants can be from the solder flux residues, handling, storage, and from user environment [41; 46-49]. Critical humidity levels of some of the common ionic contaminations found on PCBA surfaces have been reported for example 84% for glutaric acid, 75% for NaCl, 29% for $CaCl_2$, and only 11% for LiCl [50]. Recently, number of papers [2-6] have reported corrosion failure due to contamination on PCBAs, and especially from NaCl.

Overall the work shows the importance of enclosure material and openings on the humidity build up inside the enclosure, which depending on the conditions can reach levels higher than the critical point for corrosion failures. The data shown in this paper can be used for prediction as shown by the RC modelling to determine the relative moisture effects without more complex fluid flow modelling.

V. Conclusion

1. Exposure of the PC enclosures to 98% RH at 25 and 60 ˚C gave time constants values of 6 and 2 days respectively for the moisture ingress into a thigh enclosure. The presence of 1 mm hole, Gore vent, 3 and 10 mm hole in the casing wall has reduced the time constants to (3.5 and 1.6 days), (4.8 days and 1.6 days), (1.2 days and 19 h) and to (4.5 and 2 h) respectively at 25 and 60 ˚C.
2. Sorption tests showed that moisture saturation of 3 mm thick PC walls has been reached in 5 days at 25 ˚C and 1 day at 60 ˚C. The diffusion through the PC walls had a large contribution in the moisture ingress in the enclosures with a leak size less than 1 mm diameter.
3. Experiments and RC modelling showed that the release of moisture from the polymer walls can lead to a saturated humidity level and even to condensation inside the enclosures, depending on the properties of the polymers (solubility and diffusion coefficients) and the volume of the enclosure.
4. In presence of NaCl surface contamination, increase of leak current on SIR PCB pattern inside the enclosures appeared when the moisture ingress reached 70-75% RH. This level can be reached in 4.4 and 1.3 days in a tight PC enclosure exposed to 25 ˚C and 60 ˚C, and will be reduced to 2.2 and 1.0 days with a hole of 1 mm diameter in the casing wall.

Acknowledgements

This work was supported in part by the Danish Council for Independent Research, Technology and Production Sciences through the ICCI Project and in part by the Innovation Fund Denmark through the IN-SPE Project. The authors would like to acknowledge the commitment and help of the industrial partners.

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