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Moisture Ingress into Electronics Enclosures under Isothermal Conditions

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Abstract. The number of electronics used in outdoor environment is constantly growing. The humidity causes about 19 % of all electronics failures and, especially, moisture increases these problems due to the ongoing process of miniaturization and lower power consumption of electronic components. Moisture loads are still not understood well by design engineers, therefore this field has become one of the bottlenecks in the electronics system design. The objective of this paper is to model moisture ingress into an electronics enclosure under isothermal conditions. The moisture diffusion model is based on a 1D quasi-steady state (QSS) approximation for Fick's second law. This QSS approach is also described with an electrical analogy which gives a fast tool in modelling of the moisture response. The same QSS method is applied to ambient water vapour variations. The obtained results are compared to an analytical solution and very good agreement is found.

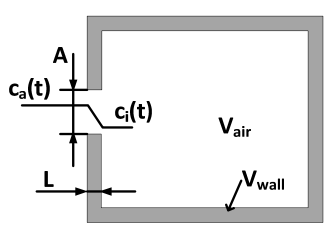
INTRODUCTION

Nowadays, the number of electronics used in outdoor applications is constantly growing. Its deployment in climatically harsh environment creates a significant challenge for engineers to design reliable and durable electronic devices and systems. As a consequence, the harsh environment drives a range of moisture related failure mechanisms: acceleration of corrosion, leakage currents, alternation of material properties, electrolytic metal migration causing short or open circuits [1-3]. Moreover, the importance of moisture problems tends to increase due to miniaturization of electronic devices and lower power consumption [4]. Secondly, there is little known about the moisture load inside electronics and how to predict its lifetime in humid conditions. Therefore, development of moisture transfer models is highly important for usage in the early and final stages of electronics design. Such models can be used for estimating the lifetime under known operating (humidity and temperature) conditions, materials selection for electronics packaging, and consequently using proper moisture controlling techniques.

There is a number of paths for moisture ingress into enclosures and packages such as cracks, openings, and permeable walls [4-5]. Thus, the objective of this paper is to discuss the moisture ingress through an opening into electronics enclosures when exposed to constant and variable ambient humidity under isothermal conditions.

MOISTURE RESPONSE INSIDE AN ENCLOSURE TO A STEP CHANGE IN AMBIENT VAPOUR CONCENTRATION

Let us consider an electronic enclosure which has an opening and is made from plastic (Fig. 1, a). The volume of the enclosure is air-filled and it is connected to the ambient atmosphere through the opening.



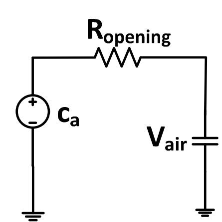


FIGURE 1. (a) Enclosure with a hole for moisture ingress and (b) electric analogy

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In order to model the moisture response inside the box, in the present work the so-called QSS model is used, which is originally derived by Tencer [5]. The model represents Fick's first law and can be applied to a constant vapour concentration under the following assumptions:

- Convection of air inside the opening is neglected, and therefore the mass is only transported by diffusion.
- The temperature is the same everywhere and is not changing during the moisture transport.
- The diffusive flux is the same everywhere inside the opening at a given time.

The diffusive flux Q' (kg/s) passing through an opening is expressed by:

$$Q^{'} = -DA\frac{c_i(t) - c_a}{L} \tag{1}$$

where L is the hole or wall thickness (m), A is the surface area of the opening (m^2), c_a is the ambient water vapour concentration (kg/m^3), and c_i is the interior water vapour concentration (kg/m^3).

The first-order differential equation for moisture transport is now given by:

$$V_{air}\frac{dc(t)}{dt} = \frac{c_i(t) - c_a}{R_{opening}} \tag{2}$$

where V_{air} is the volume of the cavity (m^3). The solution to equation (4) (when the initial vapour concentration is not zero) is given by:

$$c_i(t) = c_a - (c_a - c_{0i})e^{\frac{-t}{\tau}} \tag{3}$$

where the resistance and time constant are:

$$R_{opening} = \frac{L}{DA} \tag{4}$$

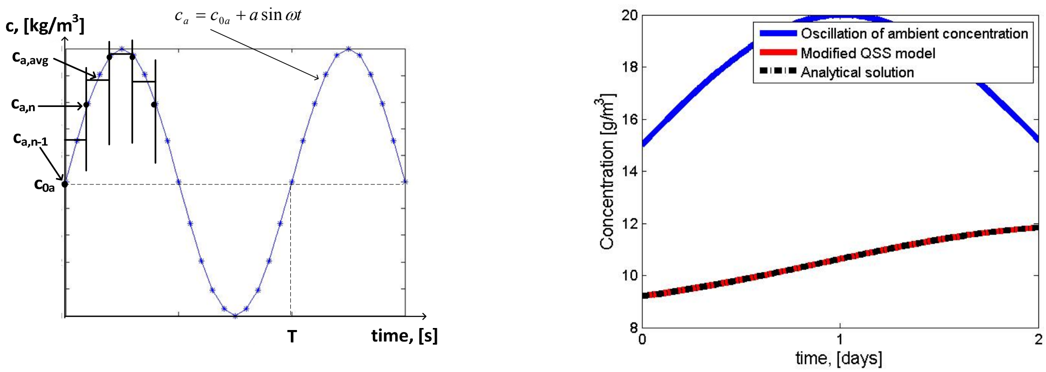
$$\tau = \frac{V_{air}L}{AD} = V_{air}R_{opening} \tag{5}$$

The QSS model for diffusion has its electrical analogue of charging or discharging a capacitor through a resistor, which has been illustrated in Fig. 1. b. The product of resistance and capacity gives the time constant which describes the response time for a system.

MOISTURE RESPONSE TO VARIATIONS OF WATER VAPOUR CONCENTRATION

This section discusses the behavior of the moisture response (c_i) subjected to a variable ambient humidity (c_a) using a modified QSS model. The relation between frequency of the ambient humidity and the system's time constant will be discussed to find out how the interior humidity follows the changes in the ambient humidity.

In order to estimate the response of the moisture to the ambient humidity variations, first, a simple sinusoidal function is chosen to describe the changes of the humidity (blue curve in Fig. 2, a). The sinusoidal function is used due to its simplicity and existence of a closed form analytical solution (for validation of the QSS model).



(a) (b)

FIGURE 2. (a) Curve of ambient humidity which is divided into small time step intervals, (b) Comparison of the analytical solution and the modified QSS model. Here ω is the oscillation's angular frequency (rad/s), a is the oscillation's amplitude, and c_{0a} is the initial offset amplitude (kg/m^3).

In reality, a curve emulating the humidity changes is more complex and can be expressed as a Fourier series of the sinusoidal oscillations, however, to avoid the complexity in modelling the concentration curve can be divided into small time intervals. If the concentration is assumed to be constant in each interval, the quasi-steady state (QSS) model can be applied for simulating the moisture response. In each time intervals, the average constant concentration value can be estimated (Fig. 2, a):

$$c_{a,avg} = \frac{c_{a,n} + c_{a,n-1}}{2} \tag{6}$$

and this average concentration is inserted into the differential equation (2) and (3), which finally becomes:

$$c_i(t) = c_{a,avg} - (c_{a,avg} - c_{0i,n-1})e^{\frac{-(t-t_{n-1})}{\tau}} \tag{7}$$

where $c_{0i,n-1}$ is the initial concentration of the previous interval (kg/m^3), and t_{n-1} is the total time after the previous interval (s).

The analytical solution can be derived from equation (7) when the sinusoidal function is substituted into the differential equation (2):

$$\frac{dc_i(t)}{dt} + \frac{1}{\tau}c_i(t) = \frac{1}{\tau}\left(c_{0a} + a\sin\omega t\right) \tag{8}$$

Equation (8) is a first order nonhomogeneous linear differential equation, and the response of the interior humidity to the oscillations in the ambient humidity (when $c_{oi}\neq 0$ and c_{oa}) becomes:

$$c_i(t) = c_{oa} + \left((c_{oi} - c_{oa}) + \frac{a\omega}{\tau\left(\omega^2 + \frac{1}{\tau^2}\right)}\right)e^{(-t/\tau)} + \frac{\frac{a}{\tau}\left(\frac{1}{\tau}\sin\omega t - \omega\cos\omega t\right)}{\left(\omega^2 + \frac{1}{\tau^2}\right)} \tag{9}$$

Defining an angle φ:

$$\frac{1}{\tau\sqrt{\omega^2+\frac{1}{\tau^2}}}=\cos\varphi \quad \text{and} \quad \frac{\omega}{\sqrt{\omega^2+\frac{1}{\tau^2}}}=\sin\varphi \tag{10}$$

This modified model was developed as a code in Matlab and validated with the analytical solution (Eq. 9). Figure 2. b shows that the results are in good agreement with the analytical solution (Eq. 9). In this case, the time step for discretizing the curve was chosen to 1000 s.

Based on equations (9) and (10) when the frequency is high compared to the system's time constant ($\omega >> 1/\tau$), the interior moisture oscillations are very small and it responds to the average value of the ambient concentration. However, when the humidity changes are very slow ($\omega << 1/\tau$) the interior humidity follows the ambient humidity curve. Thus, the phase shift φ varies between 0 and 90° and represents the interior moisture response behavior compared to the ambient humidity.

CONCLUSIONS

- The discussed QSS model for an opening can be used for an enclosure with aluminum walls (due to its impermeability). However, this model can also be applied for moisture transport through the hydrophilic walls and for complex geometries which will be discussed more in details in future works by the authors.
- The modified QSS model is applicable for any curve which characterizes the humidity variations. Moreover, this method is more convenient to use than expressing any periodical humidity changes as the Fourier series of sinusoidal oscillations and hence finding the corresponding analytical solution.

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