Investigation of Moisture Ingress and Egress in Polymer – Glass Laminates for PV Encapsulation

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Abstract

The combinations of different and time-varying environmental conditions affect PV modules operating outdoors, both instantaneously and by causing different types of long-term performance degradation and failure modes. Among the most crucial environmental stressors for long-term effects is moisture ingress. Moisture reacts with the back sheet, encapsulant and outer parts of the solar cells. If the encapsulant is the commonly-used ethylene vinyl acetate (EVA), moisture that has entered the laminate reacts with the VA content, producing acetic acid. This reacts with the contacts on the cells, causing corrosion and eventual negative impact on the electrical output. This work investigates the rates and patterns of moisture ingress into and egress from c-Si PV laminates as the external humidity changes, through both simulation and experiment.

1. Introduction

Moisture ingress is a very important factor for the failures that a PV module develops. The measurement of relative humidity in a PV module and its theoretical estimation is crucial. Much theoretical work has been done on predicting the relative humidity in a PV module due to moisture ingress [1,2], by applying Finite Element Analysis (FEM). However, experimental verification is limited (for a rare example see [3]). Moreover, some of the methods proposed for the measurement of local humidity are not applicable to PV modules of realistic design. The TiO_2 films mentioned in [4] are deposited on glass substrates and they are not suitable for encapsulation. The Ca films described in [5] are applicable for qualification of moisture but not for quantification. Finally, FTIR spectroscopy [6] is not so valid, as the cover glass blocks some EVA peaks from being detected. The goal of this work is the calculation of the moisture distribution within the PV laminates. Future work will build on this to include the calculation and verification of moisture distribution in PV modules that include cells.

2. Theory

Fick's diffusion laws describe the diffusion behaviour of water vapour through most polymers, according to literature [2]. Fick's first law is expressed as [7]:

$$J = -D\nabla c \qquad (1)$$

Where J represents the mass flux, D the diffusion coefficient and c the concentration.

By considering also the continuity equation for mass:

$$\frac{\partial c}{\partial t} + \nabla \cdot J = 0 \qquad (2)$$

we end up at the expression of Fick's second law:

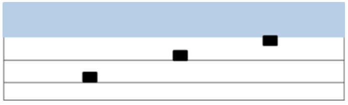
$$\frac{\partial c}{\partial t} = D\,\nabla^2 c \qquad (3)$$

For a glass – EVA – EVA – back sheet laminate, moisture ingress is dominated by penetration through the back sheet, as the contribution of ingress at the edges is minor. For the simulation of this case, the 1D solution of Fick's second law is used twice, once for the value of the diffusion coefficient of the back sheet and once for the EVA. The expression is represented [1]:

$$C(x,t) = C_S + \frac{4(C_S)}{\pi}\sum_{m=0}^{\infty}\frac{1}{2m+1}\sin[\frac{(2m+1)\pi x}{l}]e^{(-\frac{D(2m+1)^2\pi^2 t}{l^2})} \quad (4)$$

3. Experimental Setup

The experiment incorporates miniature digital humidity sensors in PV laminates during their fabrication, which are then exposed to controlled humidity levels in an environmental chamber. The samples prepared for the testing procedure are glass–EVA–EVA–back sheet structures with dimensions 20 x 20 cm. In the samples, three sensors are placed at different interfaces, one at the back sheet-EVA interface (HS1), one at the EVA-EVA interface (HS2) and one at the EVA-glass interface (HS3). The temperature in the chamber is kept at 50^{o}C and relative humidity is set to 80% for the ingress study and to 20% for the egress study.



b)

Figure 1 Glass – EVA – EVA – back sheet structure with sensors placed, at the one at the EVA-EVA interface (HS2) and one at the EVA-glass interface (HS3).

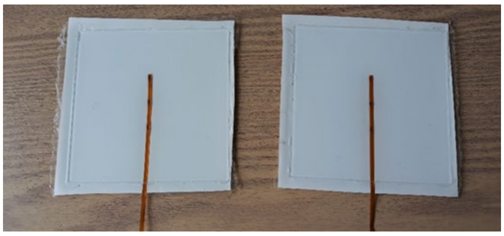


Figure 2 Laminates with the embedded sensors.

4. Moisture Ingress and Egress – Results and Discussion

For the simulation of the moisture ingress, the value of the diffusion coefficient of the EVA is taken as D_{EVA} = 1.5 x 10^{-10} m^2/s from [3]. The value of the diffusion coefficient of the back sheet is estimated to be D_B = 4.32 x 10^{-12} m^2/s, by least square fitting the measurements to the 1D Fick's law solution (applied in the dimension of the thickness of the samples). The resulting value of the diffusion coefficient of the back sheet is similar to that calculated by Jankovec et al. [3]. The simulations were carried out using COMSOL Multiphysics. The moisture ingress profile of the samples is represented in Fig. 3. It can be observed that the samples are saturated after 86 hours of aging.

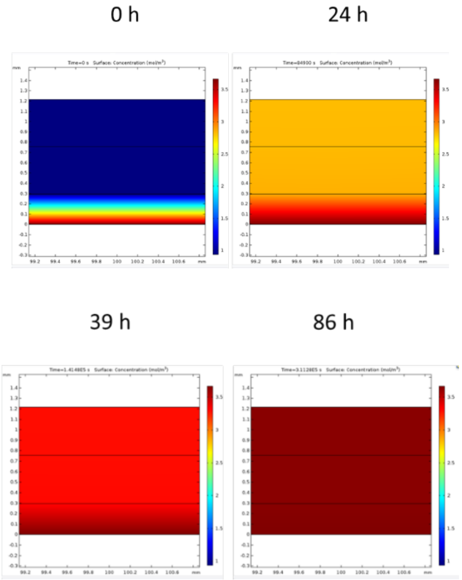


Figure 3 Moisture profile (concentration of water from 0 mol/m^3 to 3.67 mol/m^3) of the samples during ingress simulated by fitting the 1D Fick's law solution to the experimental data.

In Figures 4 and 5, both the simulation results and the measurements for each interface are plotted. The fitting of the simulated data to the actual measurements show a matched curve shape, but the simulation curve appears to underestimate moisture ingress initially by maximum 14% and then, overestimate it by maximum 9.7%. Another expected observation is that the sensors encapsulated closer to the glass (HS2 and HS3) measure the moisture ingress with a bigger delay than the sensor embedded towards the back sheet (HS1).

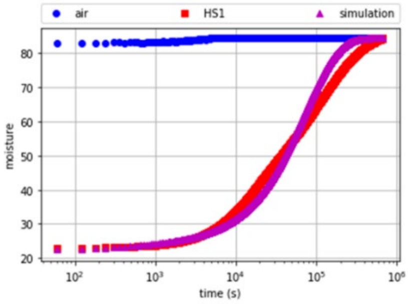


Figure 4 Measurements and simulation for the moisture ingress at the back sheet – EVA interface.

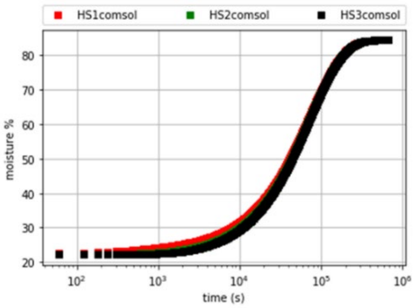


Figure 5 Simulations for the moisture ingress at all three interfaces.

The moisture egress is modelled in a similar way to the moisture ingress. The value of the diffusion coefficient for the EVA is unchanged. The value of the diffusion coefficient of the back sheet is calculated to be $D_B = 4.4 \times 10^{-12}$ m²/s, a value very close to the value calculated by the fitting for the moisture ingress simulation (1.8% difference). The time profile of the moisture egress from the samples is shown in Fig. 6. According to the measurement and the simulation results the moisture egress is a faster procedure than the moisture ingress, as it is also supported by Lin and Chen [8].

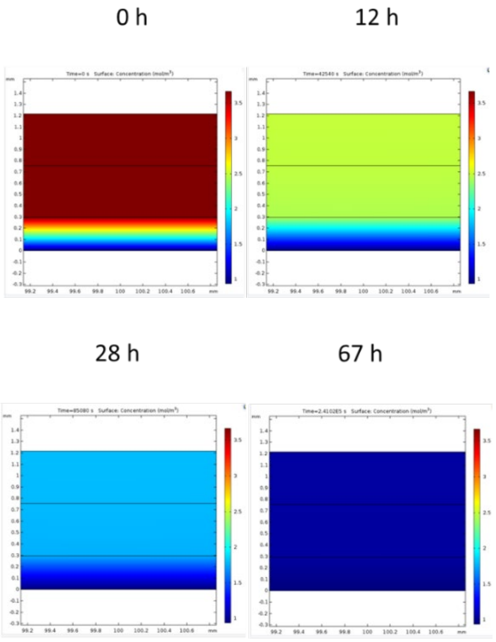


Figure 6 Moisture profile (concentration of water from 3.67 mol/m³ to 0 mol/m³) of the samples during egress simulated by fitting the 1D Fick's law solution to the experimental data.

The comparison of the simulated data to the experimental is presented in Fig. 7. The same behaviour as for the case of moisture ingress is observed (the simulation underestimates the moisture concentration by 7.9% maximum, then overestimates by 10% and finally underestimates again by 2% maximum). Moreover, in Fig. 8, a delayed moisture egress is observed for the sensors embedded towards the glass.

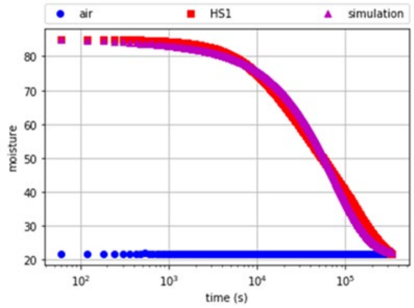


Figure 7 Measurements and simulation for the moisture egress at the back sheet – EVA interface.

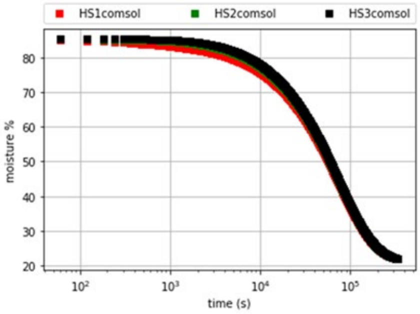


Figure 8 Simulations for the moisture egress at the three interfaces

As seen in the results section, for both moisture ingress and egress, the slope of the curve of the simulation is slightly steeper than the slope of the curve of the measurements. Two reasons could be responsible for this observation. The first reason involves non-Fickian behaviour of the polymers, meaning that the value of the diffusion coefficients of the back sheet and EVA should not be constants, but depend on the moisture concentration in the polymer [9].

The second reason responsible for this behaviour could be the measurement time response of the humidity sensor, because the humidity sensor itself measures the relative humidity according to the saturation of a polymer that is incorporated in it. In addition, this type of sensors is manufactured for measuring the air moisture content. Their behaviour for measuring the moisture content of a polymer is still under investigation.

5. Conclusions

This work analyses the moisture ingress and egress in PV laminates with structure glass – EVA – EVA – PET back sheet. From the results it is observed that moisture egress is a faster procedure than moisture ingress. In addition, for both moisture ingress and egress, the shape of the simulation curve is matched to the shape of the measurement curve, but the simulation underestimates and overestimates the moisture content for different parts of the curves. The reason behind that could be either that the non-Fickian behaviour of the polymers is not included in the simulation of moisture ingress and egress, or a delayed measurement by the sensors, something that will be identified in future work.

6. Acknowledgements

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7. References

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